Optical Gain beyond Hakki-Paoli. A new powerful tool for Reliability of Laser Diodes

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ABSTRACT

Simpler procedures for gain measurements in commercial laser diodes are introduced. They fully agree with the results of the popular Hakki-Paoli method, greatly extend its application range and remove those practical constraints that reserve practical gain measurement to the sole device designer and manufacturer. The aim of the paper is to propose the new method for reliability studies, to support and address the investigation of Failure Physics of semiconductor lasers. Some recent puzzling case histories are also summarized, that did not benefit of the new method. Their role is to point out how many unsuspected, and even unexplained physical phenomena may affect a technology that is not yet really assessed.

Keywords: Laser Diode, Gain Measurement, Reliability

1. INTRODUCTION

One of the most surprising discoveries for a newcomer entering the world of Space Technology is the abundant use, for solid-state electronic and opto-electronic devices, of Components Off The Shelf (COTS), that is of commercial devices developed for other applications. The reason is very simple: solid-state devices from mass production have achieved, along decades, extremely high levels of reliability. Commercial Integrated Circuits (IC) currently demonstrate failure rates as low as few FITs (1 FIT = 1 failure in 10^9 devices per hour), and the attempt to develop, for the same devices, dedicated process lines for low-production advanced applications (military and space) have proven since decades simply ineffective, under the Reliability point of view.

Recently, the automotive world, where electron devices every day become more and more pervasive and face an operating life in a real harsh environment, approached Space [1] by mapping the overlaps and the differences between the mission profiles, and the corresponding qualification tests, for Automotive and Space application, and showing how extended that overlap is. What qualification for automotive does not consider for electron devices, and is important for space, are those application-specific stresses as extreme thermal cycling, very low steady temperatures and radiations.

Something similar happens for solid state laser diodes, whose mass production has been, and still is, strongly prompted by telecom applications. The appeal for aerospace is evident, as clearly demonstrated also by the focus and the program of this Conference ICSO. What is different from the silicon ICs is that, on one side, monolithic integration of photonic elements has been developed only at very low scale, and on the other side physics and technology of the basic elements themselves, lasers and light emitting diodes, is still under development. The last point also means that not everything that can go wrong has been discovered; in other words: Failure Physics is incomplete for solid state light emitters. This should warn against unexpected events in missions with no repair chances, and also should strongly call for suitable effective measurement tools and procedures for monitoring the performances of a working device and for addressing diagnosis of the failing ones.

The Authors share a long lasting experience on laser diode reliability that grew in the field of telecom systems and, since more than a decade, also focused on space applications [2,3]. During their studies, they investigated the link between causes (physical failure *mechanisms*) and effects of degradations (functional failure *modes*), for the sake of lifetime prediction and technology improvement.

One of the difficulties in decoding *mechanisms* starting from *modes* comes from the current protocols, that identify in some few parameters, as the threshold current and the optical efficiency, the characterizing quantities. They are, indeed, parameters that are quite sensitive to the most of the laser diode degradations, but are a sort of metadata, depending each on a set of deeper and more fundamental quantities, as optical gain, absorption and loss. The latter, in turn, are so much closer to the physical level that their direct measurement would greatly ease the interpretation efforts in case of degradation and failure. The reason for not accessing that deeper level is that gain measurement is a difficult task for any end-user, not knowing the intimate technology of his devices.

This paper aims to summarize a new method that allows for gain measurement of laser diodes, accessible also to the end user, and not restricted to the sole manufacturer. The role and relevance of that measurement for the sake of diagnostics and reliability will be pointed out.

Some puzzling case histories will also be reported, that did not benefit of the new method, for highlighting, if ever necessary, that Failure Physics of laser diodes is, today, a work in progress.

2. LASER PARAMETERS AND RELIABILITY

2.1 Laser parameters

The proposed method [4,5] , that is going to be summarized, aims to provide the spectral measurement of

1. The absorption coefficient g_m
2. The total loss coefficient α_T
3. The gain g at any injection level

It will show gain saturation and measure its level g_{th}, as well as frequency selection for the laser regime.

2.1.1 *Ingredients*

The relevant point, on the practical side, will be the use of simple “ingredients”, all easily accessible also to the end user:

a) Some few spectra, at different injection current, in the sub-threshold regime (fig.1)
b) The DC characteristics for voltage V, current I, and optical power P_{OUT} (fig.2)
c) A single picture at the Scanning Electron Microscope (fig.3) for measuring the length L of the optical cavity.

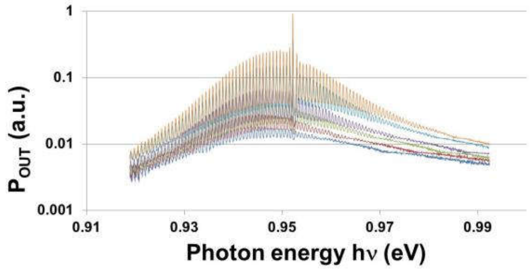

Figure 1. Optical spectra in the sub-threshold range, measured at different injection levels, for the case of a Distributed FeedBack DFB laser diode with Fabry-Perot (FP) resonances.

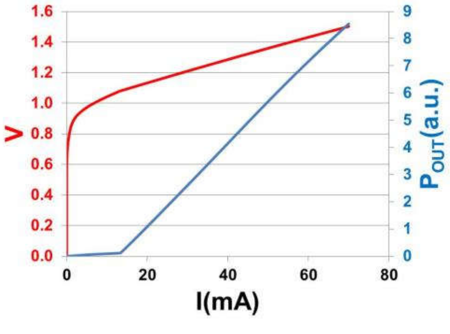

Figure 2. The DC characteristics for current I, voltage V, and optical power P_{OUT}

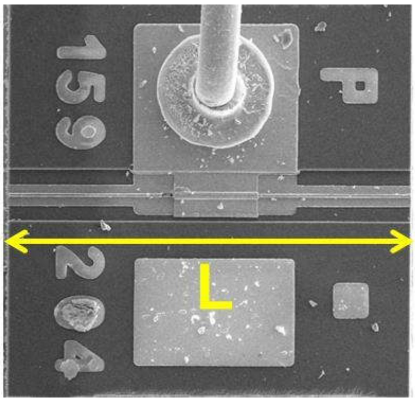

Figure 3. Measurement of the cavity length L at the SEM.

2.1.2 *Data processing steps* .

The steps for achieving the goal are:

I. Following Hakki and Paoli [6,7], calculate the envelopes of maxima and minima in each spectrum (fig.4) and their ratio r.

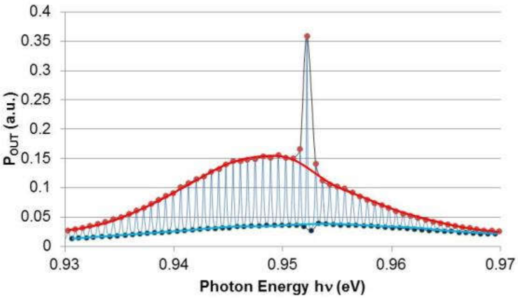

Figure 4. Maxima and minima, and their envelopes in one of the sub-threshold spectra of fig.1

II. From the differential DC electrical characteristics dV/dI, calculate the series resistance R_S (fig.5a), and then combine it with current I and voltage V to get the *junction voltage* $V_J=V-R_SI$ (fig.5b) [8]. By the way, it will display a saturation value V_{th} with deep physical significance [4,5,9]

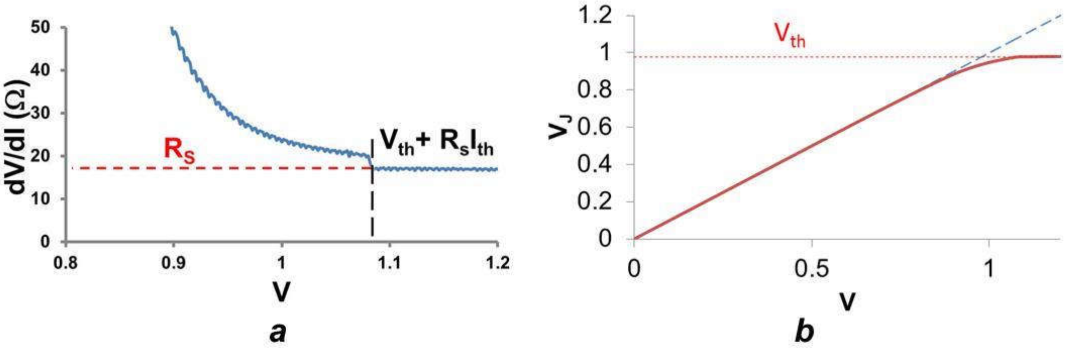

Figure 5. a) the differential plot dV/dI individuates the series resistance R_S. b) the internal voltage V_J is calculated, and represents the internal voltage of the diode junction

III. From the ratios r calculated at the point I , get the function

$$S = \ln\left(\frac{\sqrt{r}+1}{\sqrt{r}-1}\right) = L\alpha_T - Lg \tag{1}$$

and, using the V_J corresponding to the current I for that spectrum, calculate the spectral function

$$H = \frac{g}{g_m} = \frac{1-\exp\left(\dfrac{h\nu - qV_j}{2kT}\right)}{1+\exp\left(\dfrac{h\nu - qV_j}{2kT}\right)} \tag{2}$$

IV. Collect all the S_i and H_i pairs (a graphical representation is given in fig.6) and solve for the unknowns g_m and α_T by means of the linear relationship (L has been measured at the previous point c)

$$S_i = L\alpha_T - Lg_m H_i \tag{3}$$

both g_m and α_T are spectral functions.

V. Calculate gain g from eq.(1) at each of the current values at which spectra have been acquired. The joint plot of the values of g for each and all the spectra in fig.1 together with the curves for $-g_m$, g_m and α_T (fig.6) is the central result of the proposed method

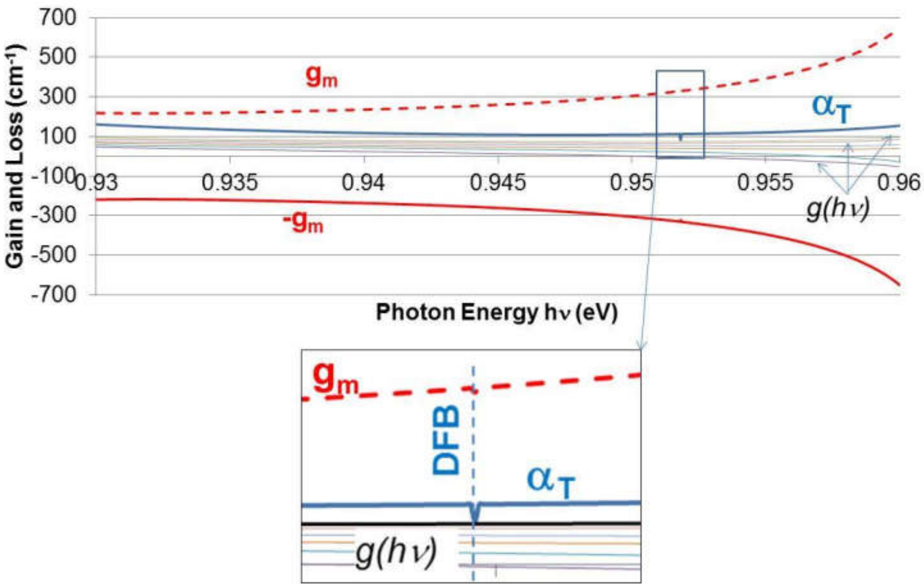

Figure 6. Experimental gain from spectra in fig.1 and its measured upper and lower boundaries. The inset expands the region where the lower DFB peak in the absorption coefficient α_T determines the gain saturation at a single frequency, inhibiting any other one from contributing to laser emission.

2.1.3 Mutual relationships among g, g_m and α_T.

From Eq.(2), g_m defines (and measures) the upper and lower limits for gain g.

The role of α_T comes out from eq.(1), that does not allow gain values larger than α_T, and sets a threshold value $g_{th} = \alpha_T$ for gain, corresponding to an infinite value of the ratio r between maximum and minimum at some frequency in the spectrum. It is the switching on of the laser regime. If $\alpha_T > g_m$, this condition can never be achieved, and the device will never be a laser at that frequency. If this holds for all frequencies in the spectrum, the device will behave, at most, as a Light Emitting Diode.

It should be noticed that the loss coefficient α_T, that in the original Hakki-Paoli method had to be measured by other independent methods, and resulted in the most severe difficulty for anybody else than the manufacturer, now comes out by two independent measurements, whose agreement is a key qualifying point of the new method: first, eq.(3) couples eq.(1), that only deals with α_T, and eq.(2), that only speaks of g_m in the subthreshold range; second, eq.(2) itself, using the full range of values of V_J , including its saturation (fig.5b), saturates itself, and its saturation must be at α_T/g_m . Reference [10] gives details of this check.

2.1.3 Physical significance of gain and loss parameters

The theoretic background [4,5] shows that:

- g_m corresponds to the absorption coefficient for the un-pumped material, no matter the shape and the boundary conditions at its edges. It is a *spectral quantity strictly related to the sole material*. It is made of a combination of slow varying functions of the photon frequency, namely the group velocity and the Einstein coefficient for the stimulated transitions, and the joint density of states for electron and holes coupled in an optical transitions, The latter introduces the sharp transition between forbidden and allowed photon energies at the bandgap.
- α_T deals with internal losses α_i, due to any loss mechanism that occurs inside the material and is NOT due to optical absorption (that is included in the definition of the gain function), and with surface losses α_m as those due to the partial transmission of light across the mirror facets, according with the simple combination rule

  $$\alpha_T = \alpha_i + \alpha_m \tag{4}$$

  It is a spectral quantity related to material defects and geometrical features of the optical cavity.
- *g,* the gain function, gives account for the balance between stimulated emission and optical absorption. As for g_m , it is in itself not dependent on defects, geometries and losses in general. Its spectral shape is only related to material properties. Anyway, it is upper bounded by the constraint $g \leq \alpha_T$. As soon as even a single point in the spectral *g* function reaches a single point in the α_T function (see inset in fig.6), gain blocks at all frequencies. In this sole way losses can affect gain: changing its saturation.

2.1.4 Relationship with threshold current and efficiency

The standard measurement of a laser diode draws the total emitted optical power P_{OUT} as a function of the injection current I (fig.7a), and individuates the threshold current I_{th} and the optical efficiency η as, respectively, the starting coordinate and the slope of the right-hand side branch of that bi-modal curve.

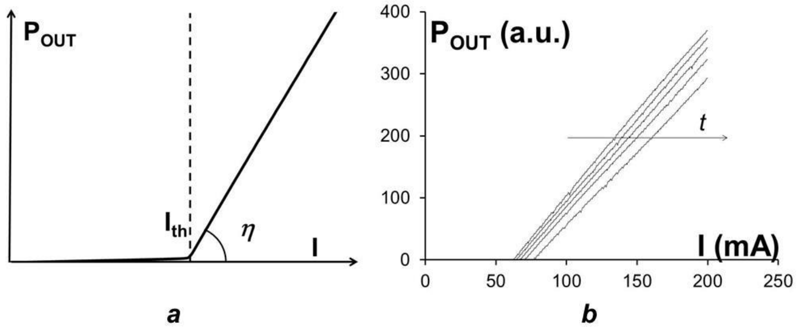

Figure 7. a) The power-current DC characteristics of a laser diode, with the identification of the threshold current I_{th} and the optical efficiency η. b) Typical time evolution during a degradation:

During degradation (fig.7b), no matter its cause, the emitted optical power decreases, and the power-current curve evolves by letting I_{th} to increase and η to decrease. Even if some kinetics could be derived from results as in fig.1b, up to predict a lifetime for the device under test, the physical cause of the degradation remains undefined.

A step forward consists in considering the mathematical form for the $I>I_{th}$ branch in fig.1a

$$P_{OUT} = \eta_T \left(I - I_{th} \right), \qquad I>I_{th} \tag{5}$$

The explicit form [11,12] of the parameters η_T and I_{th} shows the detailed links to physical and technological quantities

$$\begin{cases} \eta_T = \dfrac{h\nu}{q} \eta_q \eta_{coupl} \dfrac{\alpha_m}{\alpha_T} \\ I_{th} = I_{th0} \exp\left(\dfrac{\alpha_T}{g_0} \right) \end{cases} \tag{6}$$

where the loss coefficients α_T and α_m yet appear explicitly, while [10] demonstrated that

$$g_m = 4g_0 \tag{7}$$

The two coefficients g_m and α_T do not enter any other term in eq.(6),because:

- $\dfrac{h\nu}{q}$ is simply the conversion factor from current to power, made of the ratio between the photon energy and the electron charge;
- η_{coupl} is the coupling coefficient between the laser diode and the light collecting system. It can change only because of external causes (i.e., fiber displacement, or darkening of optical surfaces, or debris along the optical path in free space);
- η_q is the quantum efficiency, that measures the fraction of the total current that is transformed into light. It should be evident that, in the laser regime, all current beyond I_{th} is converted into light. In other words, $\eta_q = 1$.
- I_{th0} corresponds to the total current measured at transparency, that assumes also the meaning of the ideal threshold current in case of no losses. It can change because of any mechanism *not involving light* emission or absorption (increase of parasitic currents, onset of leakage paths outside of the active region, etc.)

2.1.4 Degradation modes and mechanisms

It is not the case of listing all known mechanisms and to relate them to the measured characteristics as those in fig.7. It will be sufficient to indicate some examples (Table I)

	effect on basic parameters					*degradation mode*	
degradation mechanism	α_m	α_i	α_T	g_m	I_{th0}	I_{th}	η_T
extended defects inside the actve region	0	+	+	0	+	+	-
extended defects outside the actve region	0	0	0	0	+	+	0
dopant passivation by diffusing atoms	0	0	0	+/-	0	-/+	0
mirror coating delamination	+/-	0	+/-	0	0	+/-	-/+
fiber displacement	0	0	0	0	0	0	+/-
Catastrophical Optical Damage	+	+	+	0	+	+	-

Table I . Some examples of known degradation mechanisms and of their effects on the basic parameters entering eq.6, and their ultimate effects (degradation modes) on the observable quantities I_{th} and η_T.

The second and the third line indicate that a possible observable degradation mode, involving a change in the threshold current I_{th} without any involvement of the total efficiency η_T can be originated by two completely different physical mechanisms. The availability of the proposed method, allowing to inspect the basic parameters, would solve any doubt.

3. PUZZLING CASE HISTORIES

This section is mostly uncorrelated to the previous one. It deals with three real cases, in the Authors' experience, where something new was discovered, and not always completely explained. Their role, in this paper, is to keep the alert on Failure Physics of laser diodes, because not all has been discovered. Just a summary will be given for each case, together with the reference for the extended papers specifically published on it.

3.1 Bimodal spectrum of a monomodal laser [13]

Fig.8 shows the puzzling double peak appearing in the spectrum of a DFB laser when the injection current increases.

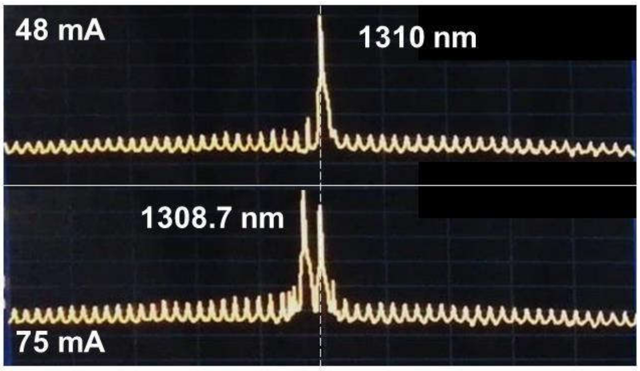

Figure 8. The double peak appearing in the spectrum of a 1310 nm DFB laser diode.

The explanation required to suppose, and then to demonstrate mathematically, that a transversal mode hopping took place, adding energy (shorter wavelength) to the longitudinal oscillation that continued to resonate with the DFB grating pitch. The reason for that transition was the partial damage of the cavity (fig.9), because of a classical Catastrophic Optical Damage (COD) that introduced a narrow stripe of defects along the longitudinal axis of the optical cavity. Defects caused the partial suppression of the fundamental transversal mode, and allowed the hopping to the second mode at high injection.

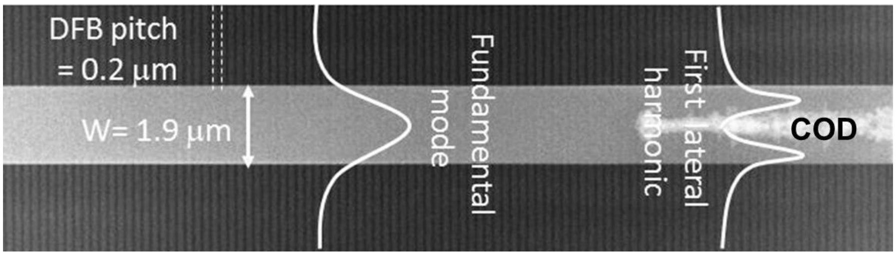

Figure 9. Transmission Electron Microscopy (TEM) top view of the COD damaged active region of a DFB.

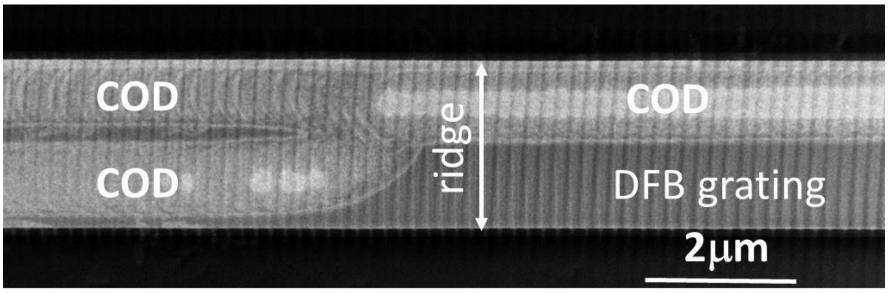

Figure 10. TEM top view of the second-harmonic COD damage in the active region of a DFB.

The result, somewhat curious but not dramatic in itself, showed that transversal harmonics, under particular conditions and sufficiently high injection , can switch on. This was the key for understanding a completely different, and much more important, situation (fig.10), where a second harmonic did indeed took place during operating life of a laser diode designed for high frequency operation. The last requirement led to reducing the area of injection and increasing the current and the photon density. This was sufficient, in some devices, to cause spontaneous mode hopping, with local maxima in the optical power so high to melt the lattice, and to leave the rails visible in the picture.

3.2 Silent damage in VCSELs after Electro Static Discharge [14]

After the qualification tests for a family of commercial Vertical Cavity Surface Emitting Lasers (VCSELs), some survived the Electro Static Discharge (ESD) test. This means that, in terms of emitted optical power, current leakage and any other parameter, they did not show any change after the test, and were then allowed to access the production line of the systems where they were employed.

It was only an anomalous image in their ElectroLuminescence (EL), a technique *not* included in the international standards for qualification o VCSELs, that some dark point were detected. The planar view TEM image of the active region showed (fig.11) local damages along the circular edge of the region itself. They were very thin, and in agreement with localized vertical sparks across the *pn* junction. Their location justified their minor impact on both the current and the optical power (see Table I) just after the test.

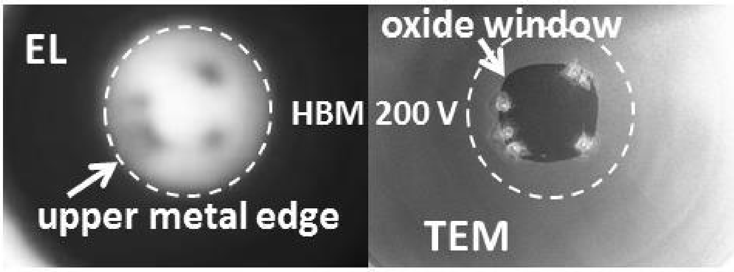

Figure 11. EL and TEM planar views of the active region of a VCSEL after an ESD test.

The relevant point is that such tiny defects are a time bomb for the device: each of them, indeed, along the operating life of the laser will become an absorption center for photons and a recombination center for electrons and holes. In other words, each defect will gain energy, and will then grow and propagate inside the active region, up to destroy the light emission (fig.12).

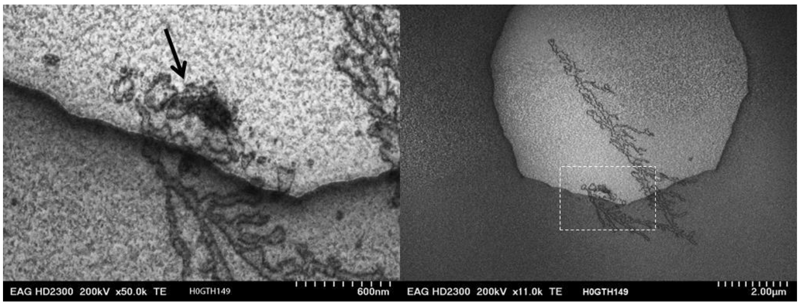

Figure 12. TEM planar views different magnification of the network of defects evolving form a small initial defect (arrowed) under operating life of a VCSEL.

3.3 Proton diffusion after radiation test [15]

An InP-based 1310 nm edge emitting laser and a GaAs based VCSEL emitting at 850 nm have been irradiated perpendicularly to the stacks of epitaxial layers. The current-power DC characteristics (as in fig.7a) have been measured before and after irradiation, showing for both devices a relevant increase of the threshold current I_{th} and a decrease of the total efficiency η. But the same measurements, repeated after some time, showed along few months a relevant time evolution, that included both enhancement and then recovery of the effects, in a different way between the two types of devices (fig.13).

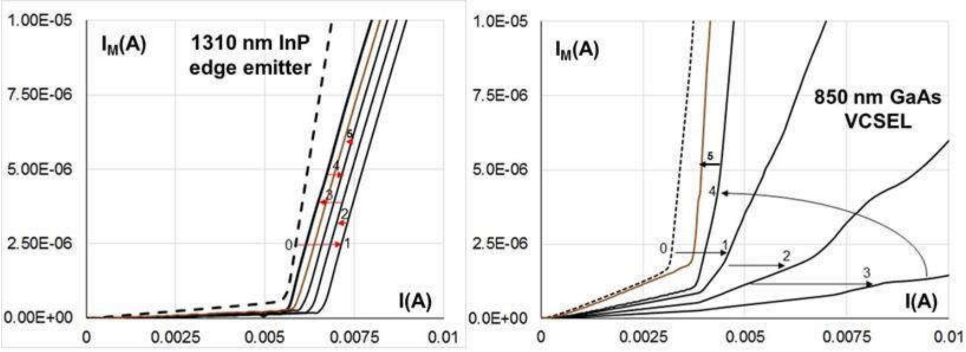

Figure 13. Power-current DC curves, evolving with time, for an edge emitter and a VCSEL irradiated with 3MeV protons.

Without entering the detailed discussion of the two cases, that introduces some hypothesis for the initial proton distribution and for their diffusion kinetics, extensively illustrated in the given reference, the key point is that, as for the previous case, something has been introduced into the devices that will evolve in time, and that should be considered when qualifying such devices for space missions.

4. CONCLUSIONS

The paper had been divided into two parts: the first proposed a method for extracting more physical information from the standard measurements, in particular by getting the gain-related parameters that link the standard laser parameter as threshold current and efficiency to, separately, material and technological properties of the devices. The second part recalls three puzzling cases that should warn against the belief that a photon device qualified for terrestrial applications can easily be employed in long-term, unrepairable missions in space. Several issues are still unclear, and Reliability Physics has still to be completed.

The Authors hope that their paper will stimulate space engineers in taking into account also the hidden challenges that photonics brings in space applications.

REFERENCES

[1] Enrici Vaion R., Medda M., Mancaleoni A., Mura G., Pintus A., De Tomasi M., “Qualification extension of automotive smart power and digital ICs to harsh aerospace mission profiles: Gaps and opportunities” Microelectronics Reliability, Volumes 76–77, September 2017, Pages 438-443. https://doi.org/10.1016/j.microrel.2017.07.061

[2] G. Mura, M. Vanzi, “The interpretation of the DC characteristics of LED and laser diodes to address their failure analysis”, Microelectron. Reliab., 50(4), pp. 471-478, April 2010.

[3] M.Vanzi, G.Mura, M.Marongiu and T.Tomasi, “Optical losses in single-mode laser diodes” Microelectron. Reliab., Volume 53, Issues 9–11, September–November 2013, Pages 1529–15

[4] M.Vanzi, G.Marcello, G.Mura, G.Le Galès, S.Joly, Y.Deshayes, L.Bechou. Practical optical gain by an extended Hakki-Paoli method. Microelectronics Reliability, Volumes 76–77, September 2017, Pages 579-583. Doi: 10.1016/j.microrel.2017.07.060

[5] Vanzi, M., Mura, G., Marcello, G., Bechou, L., Yannick, D., Le Gales, G., Joly, S. (2016). Extended modal gain measurement in DFB laser diodes. IEEE Photonics Technology Letters. DOI: 10.1109/LPT.2016.2633440B. W. Hakki, T. L. Paoli, “Gain spectra in GaAs double−heterostructure injection lasers”, J. Appl. Phys., 46(3), pp. 1299-1306, 1975.

[6] B. W. Hakki, T. L. Paoli, “Gain spectra in GaAs double−heterostructure injection lasers”, J. Appl. Phys., 46(3), pp. 1299-1306, 1975.

[7] B.W. Hakki, T. L. Paoli, “cw degradation at 300°K of GaAs double-heterostructure junction lasers. II. Electronic gain” Journal of Applied Physics 44, 4113 (1973); doi: 10.1063/1.1662905

[8] T. L. Paoli, P. A. Barnes, “Saturation of the junction voltage in stripe-geometry (AlGa)As double-heterostructure junction lasers”, Applied Physics Letters, 28(12), pp. 714-716, 1976.

[9] G.Mura, M.Vanzi, G.Marcello and R.Cao. The role of the optical trans-characteristics in laser diode analysis. Microelectronics Reliability, 53(9-11):1538-1542 · September 2013. DOI: 10.1016/j.microrel.2013.07.114

[10] M.Vanzi, G.Mura, M.Marongiu and T.Tomasi, “Optical losses in single-mode laser diodes” Microelectron. Reliab., Volume 53, Issues 9–11, September–November 2013, Pages 1529–15

[11] J. T. Verdeyen, “Gain coefficient in semiconductors”, in Laser Electronics, 3rd ed., Prentice Hall, 1995, pp.454–459.

[12] Coldren LA, Corzine SW, Mašanović ML. Diode lasers and photonic integrated circuits, Wiley series in microwave and optical engineering. Jhon Wiley & Sons, Inc., Hoboken, New Jersey; Second Edition 2012.

[13] M.Vanzi, K. Xiao, G.Marcello, G.Mura, “Side Mode Excitation in Single-Mode Laser Diodes”, IEEE Transactions on Device and Materials Reliability 16(2):1-1 · June 2016 DOI: 10.1109/TDMR.2016.2539242

[14] M. Vanzi, G. Mura, G. Marcello, K. Xiao, “ESD tests on 850 nm GaAs-based VCSELs”, Microelectronics Reliability 64 · September 2016 DOI: 10.1016/j.microrel.2016.07.023

[15] Marcello G., Mura G., Vanzi M., Bagatin M., Gerardin S. , Paccagnella A., “Proton Irradiation Effects on Commercial Laser Diodes”,Proc. 15th European Conference on Radiation and Its Effects on Components and Systems (RADECS), September 2015. DOI: 10.1109/RADECS.2015.7365649