SENRA Academic Publishers, Burnaby, British Columbia
Vol. 2, No. 3, pp. 557-565, 2008
ISSN: 1715-9997

Canadian Journal of pure & applied sciences

NEUTRON IRRADIATION EFFECTS ON DYNAMICAL CHARACTERISTICS OF VERTICAL CAVITY SURFACE EMITTING LASERS (VCSELS)

*AS Aldwayyan[1], RH Al-Hothlool[1], MS Alsalhi[1] and MYA Raja[2]
[1]Physics Department, King Saud University, PO Box 2455, Riyadh11451, Saudi Arabia
[2]Center for Optoelectronics and Optical Communications
Department of Physics and Optical Science, University of North Carolina Charlotte,
9201 University City Blvd., Charlotte, NC 28223, USA

ABSTRACT

The effects of 1 MeV neutrons irradiation on vertical-cavity surface-emitting lasers (VCSELs) characteristics are experimentally investigated. It is found that quantum efficiency of VCSELs changes as the radiation dose changes threshold current (increase of ≈ 0.3Ith). This effect is explained as a result of minorities carrier lifetime decrease. Red or blue shifts in the peak emission profile due to neutrons radiation were also noticed. Kind of shift depends on the radiation effect considered where active region temperature could increase (red shift) or the attenuation coefficient of photons in the energy gap might also increase (blue shift). Neutrons exposure may induce 'self-pulsations' in the output of some VCSELs while other devices became more stable after same dose of radiation. Knowledge of the behavior of VCSELs under neutrons radiation exposure will be useful for their applications in hostile environment.

Keywords: VCSELs characteristics, neutron radiation exposure, spectral and dynamical behavior.

INTRODUCTION

Since their emergence as commercial products more than a decade ago, VCSELs have become a viable alternate attractive light source for high speed data communication systems, low-cost transmitters in access and metro area networks, optical interconnects, optical neural networks, and optical signal processing (Langley and Shore, 1997; Raja *et al*., 2000). Today, beyond these applications, VCSELs are also being utilized to an increasing extent in radiation contaminated environment and outer-space systems (Andrieux *et al*., 1999). When an energetic photons, neutron or charged particle enters a solid, it interacts with the electrons and the atomic nuclei depending on its type and energy (Andrieux *et al*., 1999; Jiang *et al*., 2003). In past work, we also studied the effects of gamma irradiation on the characteristics of similar type VCSELs that is referred later on in the following sections.

Neutrons interfere and interact only when approach the nuclei since they are neutral particles. Three kinds of interaction may occur depending on the type of effects. Those include; (a) the transient ionization effects leading to electron-pair production and subsequently electronic currents, (b) long term ionization effects resulting in trapping centers, and finally (c) displacement effects or bulk damage. Last effect is responsible for laser diode degradation due to existence of different types of defects (Beringer *et al*., 1997). Defects change impurities concentrations, hence adding additional new energy level within the energy bandgap to work as non-radiative recombination centers. These energy states lead to the following (Beringer *et al*., 1997):

(a) *Carrier removal*: Majority carrier density is reduced by the radiation fluence.
(b) *Mobility degradation*: The mobility is found to decrease with increasing the radiation fluence.
(c) *Conductivity modulation*: Since the carrier concentration and mobility both decrease with radiation, then the conductivity will also decrease.
(d) *Minority carriers' lifetime*: The degradation rate in minority carrier lifetime is expressed as (Mommsen, 1997):

$$d\left(\frac{1}{\tau}\right)/d\Phi = k_{\tau} \tag{1}$$

Where, Φ is the total irradiation flux, K_{τ} is the carrier lifetime damage constant.
Relative relation between minority lifetime before (τ_o) and after (τ) irradiation is
given by Mommsen (1997) and Barnes (1985):

$$\left(\frac{P_o}{P}\right)^{\frac{2}{3}} = \frac{\tau_o}{\tau} \tag{2}$$

Where P_o is pre-irradiation light output and P is light output after irradiation.

τ_o can be reduced by increasing the recombination processes through increasing the impurity concentration

*Corresponding author email: dwayyan@ksu.edu.sa

in the active region and by operating the device at high current densities. Fortunately, τ_o for VCSELs (can be controlled by stimulated emission) is much lower than edge-emitting lasers, so that higher doses of radiations are needed to have noticeable changes in (τ_o/τ).

On the other hand, the presence of defects in the active region of the laser chip (due to irradiation) causes the threshold current to increase as a result of having to compensate for the injected charge that is lost through non-radiative transitions (Gill *et al*., 1998). Irradiation-induced degradation rate of threshold current (K_I) can be expressed as (Lee *et al*., 1999):

$$K_I\Phi = \frac{I_{th} - I_{th,o}}{I_{th,o}} \tag{3}$$

Where $I_{th,o}$ and I_{th} are the threshold currents before and after irradiation respectively. Threshold current could increase under irradiation up to a value beyond the maximum allowed values of operating current (Berghmans *et al*., 2002). However, original threshold values and other characteristics of VCSELs might be healed by annealing or even by operating the laser at high biasing currents for relatively long time (Camparo *et al*., 1992).

Increase in the nonradiative recombination, due to defects, leads to temperature rise in the active region, hence decreasing the energy bandgap. So that, a red shift in laser emission spectrum is expected after irradiation (Gregor *et al*., 2000). Blue shift may occur also, which can be understood as follow; defects due to irradiation increase the attenuation coefficient of photons at an energy lower than the bandgap (E_g) because of absorption in semiconductor material (due to shallow defect levels); such that gain-peak shifts to higher energy, i.e. shorter wavelengths. In fact, increase of the attenuation coefficient occurs at high dose of neutron irradiations (10^{15} n/cm^2) (Gregor *et al*., 2000). Another interpretation of blue-shift in laser emission spectra is possible which can be summarized as follow: new state (called trapping state) appears within E_g due to irradiation by neutrons in

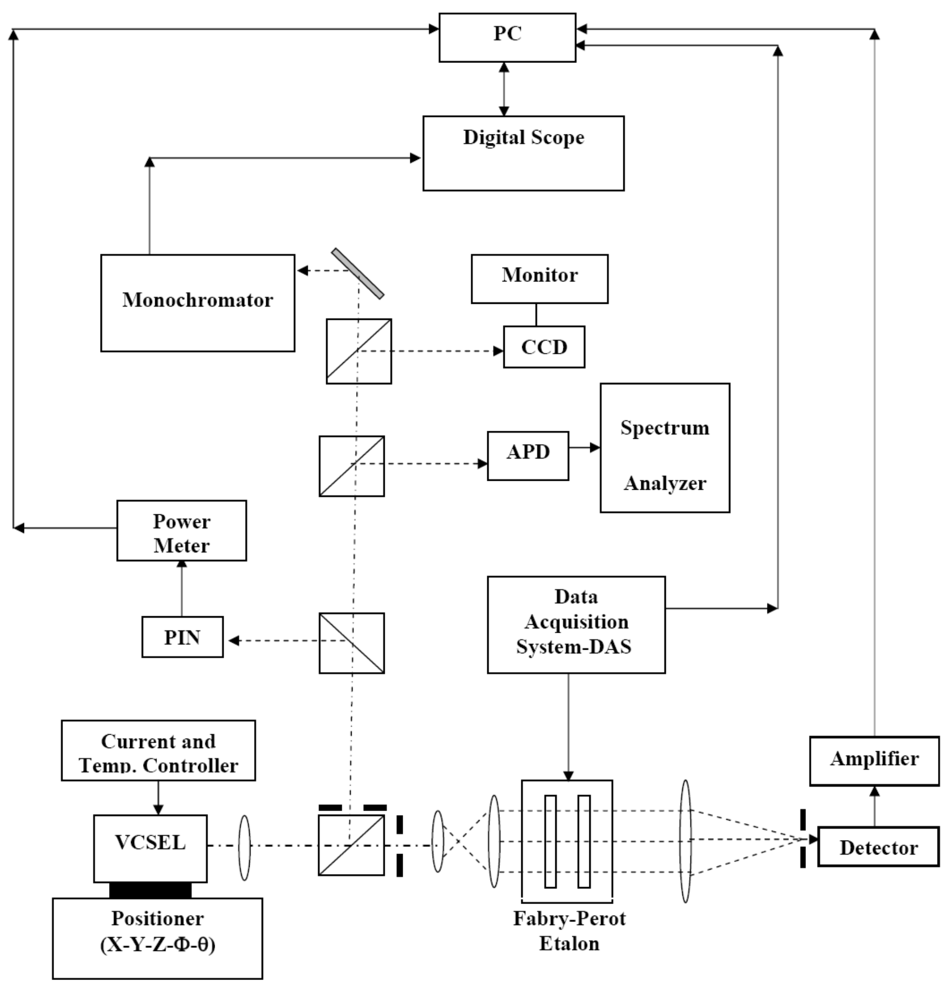


Fig. 1. A schematic diagram of the experimental setup.

the active region; this increases minority carrier density which in turn increases conduction-band energy leading to blue shift (Camparo *et al*., 1992).

There are very few reports on the effects of neutron irradiation on dynamical characteristics of VCSEL's with increased utilization of them in various applications involving exposure to the neutrons environment such as in space applications. It was shown (Gill *et al*., 1997) that signal to noise ratio for VCSEL's has not changed after neutron irradiation with dose of $1\text{x}10^{14}$ n/cm^2.

In this work, various characteristics (static, spectral shifts and polarization, dynamical behavior and temperature effects) have been experimentally investigated for VCSEL's from different batches under various doses of neutrons radiation up to10^{15} n/cm^2. The rest of the paper is organized as following; section 2 outlines the experimental details and is followed by section 3 which summarizes the main results and discussions in various subsections. Finally, section 4 concludes the paper with remarks pertaining to the experimental observations and possible physical effects.

MATERIALS AND METHODS

Experimental Details

Figure 1 shows a schematic diagram of our experimental setup. VCSELs used in this work were over seven years' old oxide-confined devices (MODE, an Ex-Division of EMCORE Corp. Albuquerque NM). Fabrication details of these devices were described in previous work (Aldwayyan *et al*., 2004). They were packaged in TO-Cans with gold coated windows. An active material wafer structure consisted of GaAs/AlGaAs quantum- wells sandwiched between epitaxially-grown distributed Bragg reflectors. The device (typical) aperture sizes ~10×10 μm^2 became smooth-edged squares (almost circular) whose actual size is effectively smaller than 10 μm in diameter. The metallization and dicing process was the standard fabrication technology that is commonly followed by the industry and most research labs. On the operation side, typical threshold current is few mA and varies from device to device by as much as 10 to 20%. These devices are predominantly single longitudinal-mode and often operate in fundamental or low-order transverse modes at relatively high biasing currents.

VCSELs were driven by current controller (LDC 500 Thorlabs, Inc. USA) with setting accuracy of ±0.2 mA. Temperature was controlled by a temperature controller (model 320, Light Control Instruments, USA) with stability of $\leq 0.01^{o}$ C. The two orthogonal polarization modes were separated by 'Wollaston prisms' and detected by an avalanche photodiodes (Thorlabs, Inc., APD 110). A digital sampling scope (Tektronix, TDS 380-Digital Oscilloscope) was used to record a large number of truly random sampled data points of intensity pulsation, collected by the photodetector. Laser emission spectra was recorded using 2 m double pass length spectrophotometer (Jobin Yavon Inc.) with diffraction grating of 1200 line/mm. Transverse modes and polarization instability were recorded by CCD camera and high resolution monitor.

A ^{238}Pu-Be neutrons source was used in which Plutonium releases α particles to collide with Beryllium atoms which in turn ejected neutrons of 1 MeV. Source radioactivity was 36 Ci with neutrons flux of 10^7 n/cm^2.sec. Measured radiation dose from the source was 550 μ Sv/h at a distance of 1 m. VCSEL's were placed at the end of 1 m portable rod 0.5 – 2 cm away from the source which was surrounded by 1 m thick of paraffin wax. Relative weak flux of the source was compensated by exposing the lasers for longer times. Thermo Luminance Detector (DLT) was used routinely for safety precautions purposes.

RESULTS AND DISCUSSIONS

As mentioned in the introduction section, VCSELs characteristics that were investigated included, dc-LI, spectral and dynamical characteristics. The characteristics were studied prior to and after the different doses of neutron irradiations. Systematic measurements were done after at least one day following the irradiation. During irradiation process, VCSELs devices were unbiased and their terminals were connected to each other (shortened to a common ground) in order to avoid any static charge that might build-up during handling for irradiation.

1. LIGHT-CURRENT CHARACTERISTICS

Table 1 summarizes the procedures detail when exposing VCSEL#1, for example, to neutron radiation. After each round, all characteristics were measured for reference.

Table 1. Doses of neutron radiation used for VCSEL#1.

Round	Radiation Time	Accumulated Time	Radiation Flux (n/cm^2)
1	0.25 h	0.25 h	$2.57\text{x}10^9$
2	0.50 h	0.75 h	$7.70\text{x}10^9$
3	1 h	1.75 h	$1.80\text{x}10^{10}$
4	2 h	3.75 h	$3.85\text{x}10^{10}$
5	8.25 h	12 h (0.5 day)	$1.23\text{x}10^{11}$
6	2 days	2.5 days	$6.16\text{x}10^{11}$
7	7 days	9.5 days	$2.34\text{x}10^{12}$
8	14 days	23.5 days	$5.79\text{x}10^{12}$
9	40 days	63.5 days	$1.56\text{x}10^{13}$
10	37 days	100.5 days	$2.47\text{x}10^{13}$
11	30 days	130.5 days	$1.43\text{x}10^{14}$

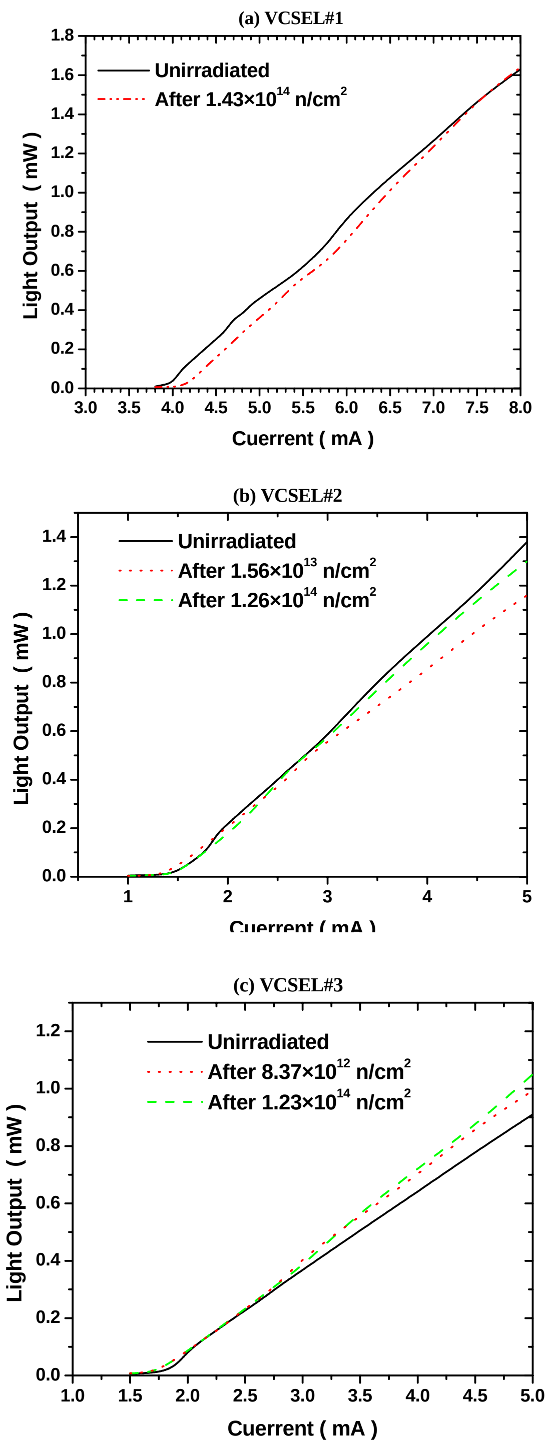


Fig. 2. L-I characteristics after exposure to selected values of neutron radiation dosage

Figure 2 shows typical L-I characteristics of the same VCSEL#1 after selected values of neutron radiation doses. Considerable increase in the laser threshold current (1.3xI_{th}) and efficiency can be noticed due to irradiation with $1.43x10^{14}$ n/cm^2, Figure 2a. VCSEL#2 on the other hand, showed a different behavior. Although a considerable decrease in the quantum efficiency can be noticed after $1.56x10^{13}$ dose of irradiation, VCSEL#2 can be almost reversed back to its original level of power efficiency if VCSEL was irradiated with dose of $1.43x10^{14}$ n/cm^2. Very little or no change in the threshold current and the quantum efficiency can be noticed after such dose of irradiation, figure 2b.

An increase in the laser efficiency can be noticed for VCSEL#3 after $8.37x10^{12}$ doses of radiation or more, Figure 2c. A "burn-in" effect (annealing) might be the reason of having higher light output of some select devices after some doses.

Temperature dependence of threshold current at two levels of doses has been recorded for VCSEL. Fig.3 shows the well-known relation between the threshold current and temperature of VCSEL#1 above a relatively short range of temperatures. VCSEL became more sensitive to temperature after being irradiated with $1.43x10^{14}$ n/cm^2.

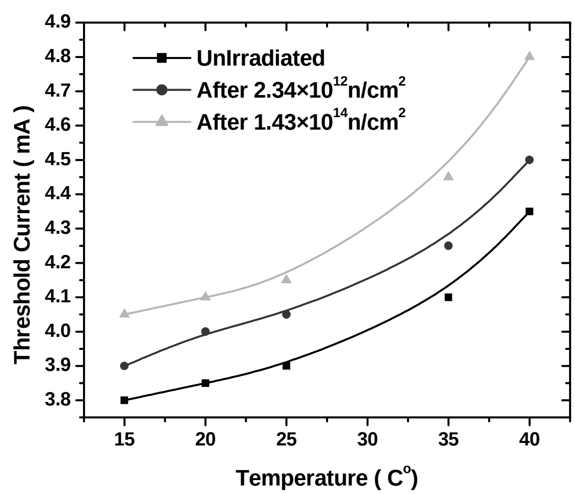


Fig. 3. Temperature dependence of threshold current at two levels of irradiation doses as compared to unexposed VCSEL

Values of threshold current can be extrapolated from the L-I characteristics. Threshold currents increase for this VECSEL with radiation doses as a result of having to compensate for the injected charge that is lost through non-radiative transitions. However, in addition to the role of radiations, temperature increase will act as a major factor in threshold current changes.

2. SPECTRAL MEASUREMENTS

Neutron-irradiation is found to induce significant spectral shifts in the peak wavelength of emission in VCSEL's in inhomogeneous fashion, depending on VCSEL's structure. Values of such shifts depend on radiation dose applied to the tested VCSEL's. Each VCSEL showed different sensitivity to radiation from the other according to their constructions. As an example, figure 4 shows the variation of peak wavelength (λ_p) over a relatively wide range of bias currents for VCSEL#2 at various radiation dose-levels. The variation trend of λ_p with biasing currents remains the same before and after irradiation. Red shift of λ_p was observed in VCSEL#2 outputs after the 1st and 2nd doses then blue shift occurs after the 3rd dose of irradiation. VCSEL#3 showed another behavior, Figure 4b. Blue shift of λ_p was observed before red shift. As mentioned earlier, blue-shift irradiation increase the attenuation coefficient of photons at an energy lower than the bandgap (E_g) because of absorption in semiconductor material, such that gain peak shifts to higher energy. As well known, temperature plays more important role in wavelength variation of emission than any other parameters. As temperature increases λ_p increases due to band gap decreasing as mentioned earlier. After each dose, temperature dependence of λ_p has been recorded for all VCSEL's. They showed same trend of variation as the current changes but with larger steps of shifts. Fig. 5 shows such effect after two radiation doses for VCSEL#3.

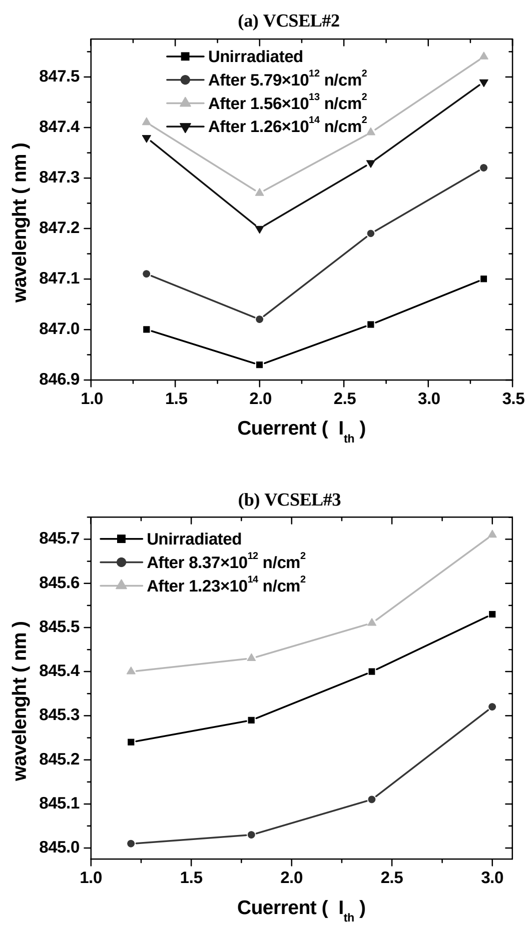


Fig. 4. The variation of peak wavelength (λ_p) of neutron irradiated VCSELs over a relatively wide range of bias currents for two VCSELs (#2 and 3)

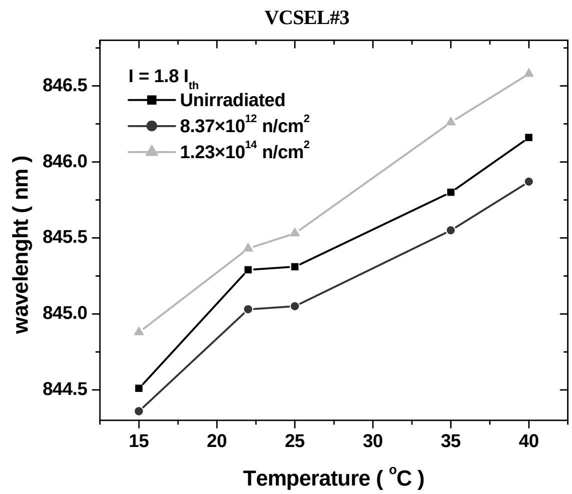


Fig. 5. The effect of temperature on wavelength shifts on the un-irradiated and irradiated (at two different neutron irradiation doses) VCSEL#3

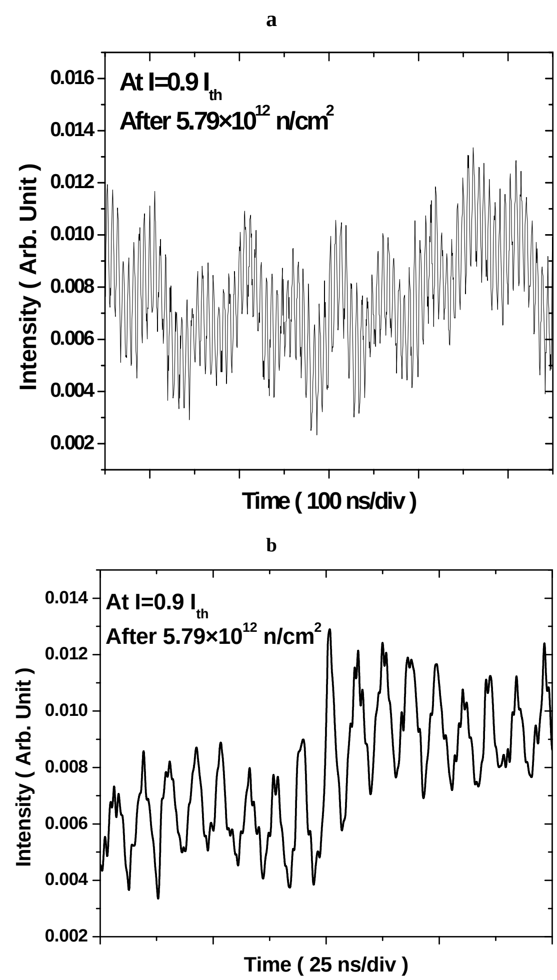


Fig. 6. Examples of the waveform of the LFP and HFP in time domain for VCSELs irradiated and operated from 0.9 Ith through 2.5 I_{th}

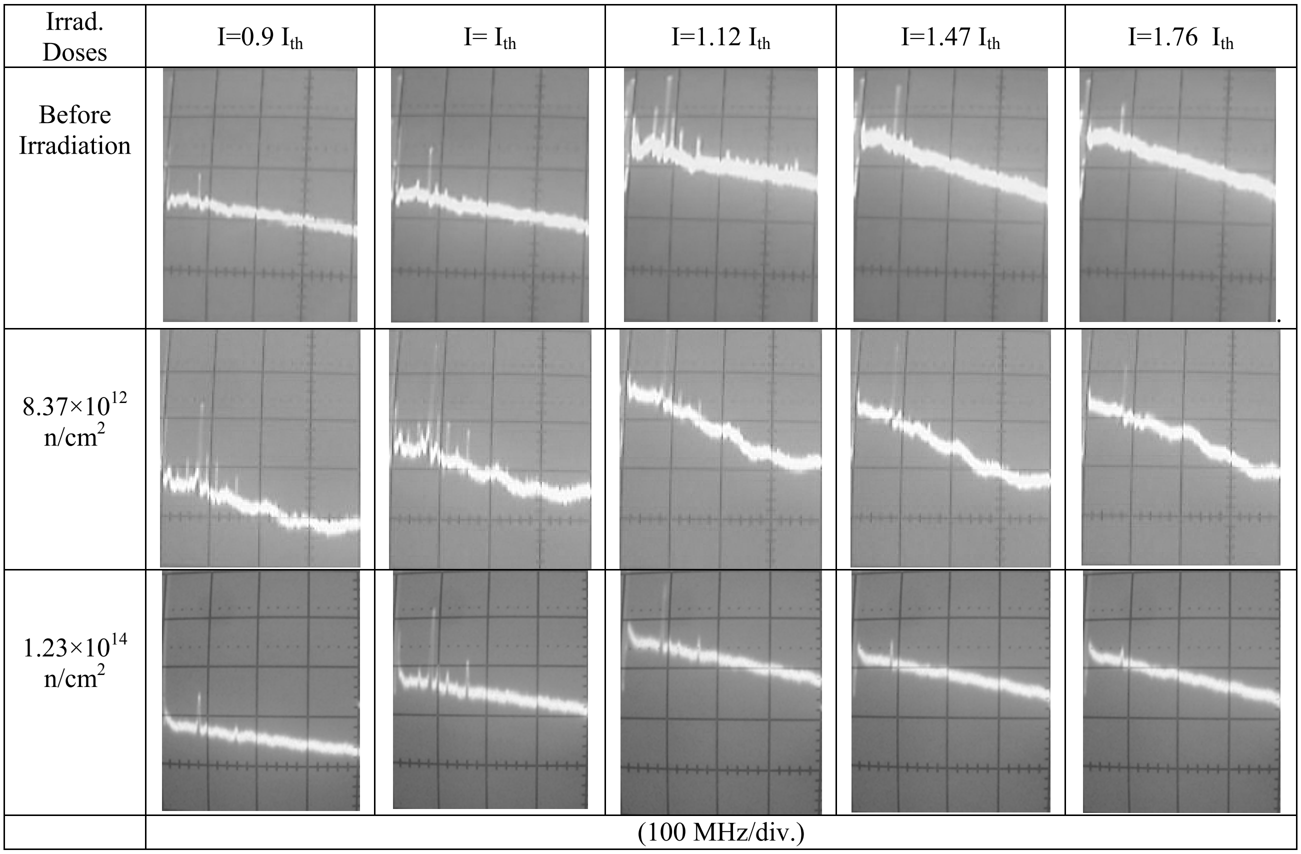


Fig. 7(a). The traces captured by the spectrum analyzer for LFP and HFP before and after irradiations at various levels of biasing current for VCSEL#3

3. DYNAMICAL CHARACTERISTICS

There are various kinds of dynamical instabilities or noise phenomena that appear in VCSELs and which were a motivation for including low frequency pulsation (LFP ~kHz to tens of MHz) and high frequency pulsation (HFP ~ 100 MHz to GHz) investigations. In LFP the frequency range of hundreds kHz up to tens of MHz, is observed in the VCSELs output intensity (Aldwayyan *et al*., 2004; Joanne *et al*., 1997). The higher photon density in VCSELs leads to higher nonlinear gain, which is known to cause general damping of photon density oscillations, including mode-partition noise (MPN) which is thought to be the main source of intensity instability (Wilmsen *et al*., 1999). The basic physical mechanism for this phenomenon is spatial hole-burning with modes competing for the same spatial carrier reservoir. Transverse modes can have different polarization, but still MPN among different transverse modes is mostly caused by spatial effects (Joze Mulet Pol, 2002).

As far as we know, no previous work has been done on the effects of neutron radiation on dynamical characteristics of VCSELs. Preliminary experimental results of dynamical instability of VCSELs under neutrons irradiation, at room temperature, are presented. LFP and HFP in the output of all used VCSELs have been observed over wide ranges of frequency (kHz-400 MHz) and current ($0.9 \times I_{th}$ to $2.5 \times I_{th}$). Both types of pulsations exist before and after irradiation dose and found to start switching just before threshold currents.

Figure 6 shows typical examples of the waveform of the LFP and HFP in time domain, which have been observed in the output of some VCSELs at $0.9 \times I_{th}$ after radiation dose of 5.79×10^{12} n/cm^2. HFP waveform is modulated by the LFP one. Because of the irregularity and randomness in the time domain, presenting the LFP in the frequency domain gives a better idea about the evolution of such behavior as a function of various external parameters.

Figure 7(a) shows the traces captured by the spectrum analyzer for LFP and HFP before and after irradiations at various values of biasing current for VCSEL#3. In this VCSEL for example, pulsations with a frequency of 80 MHz appear around threshold current before irradiation and goes into complicated forms as the current increases, figure 7(a). Laser looks more stable at $1.76 \times I_{th}$ although the whole trace rises up which in fact can be an indication of the presence of deterministic chaotic operation. More instability results in VCSELs output after irradiation with dose of 8.37×10^{12} n/cm^2 while after dose of 1.23×10^{14} n/cm^2, device got more stability than the original situation before irradiation at the same current values. This behavior can be understood by inspection the longitudinal

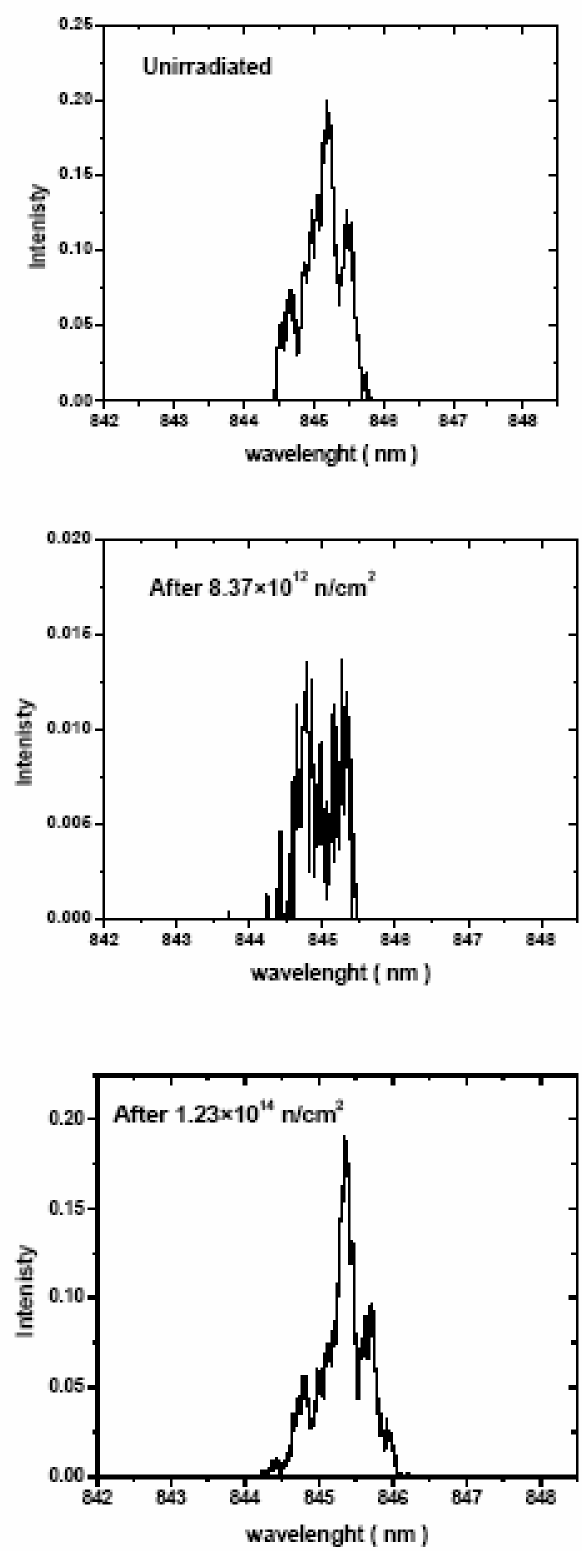


Fig. 7(b). The corresponding spectral content of the VCSEL#3 with respective operating condition as in Fig. 7(a)

spectral modes of this VCSEL, figure 7(b). One predominant mode is present before and after 1.23×10^{14}n/cm^2 dose of radiation whereas two competing modes are present after 8.37×10^{12} n/cm^2. Other VCSEL's showed same behavior. Figure 8 shows Dynamical instability of VCSEL#1 at some selected currents values. Spectral behavior is also shown at a current ($I=1.20I_{th}$) as an example, to justify the instability as a competition

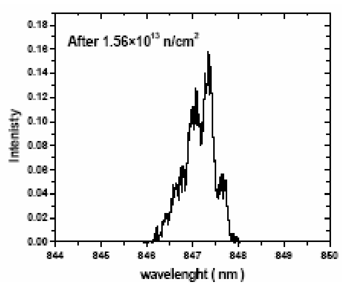
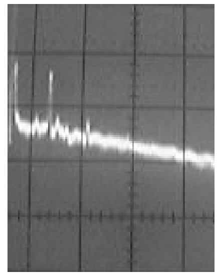
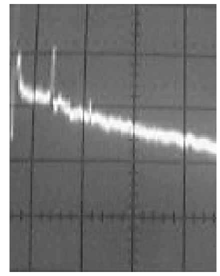
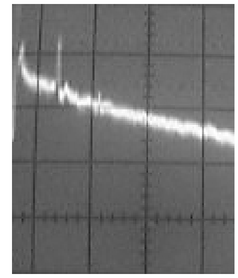
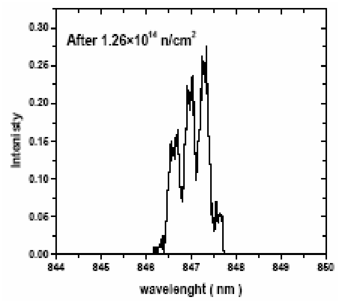
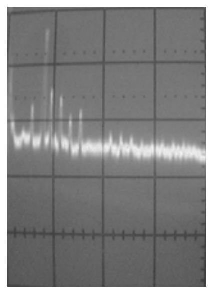
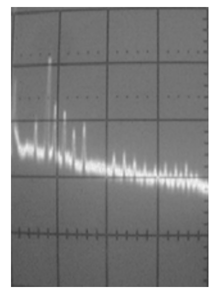
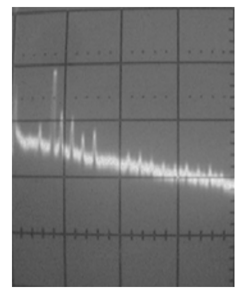
Irrad. Doses	Longitudinal Modes Spectrum at I = 1.20 I_{th}	I=I_{th}	I = 1.13 I_{th}	I = 1.20 I_{th}
1.56×10^{13} n/cm^2				
1.26×10^{14} n/cm^2				
			(100 MHz/div.)	

Fig. 8. Dynamical instability of VCSEL#1 at selected bias currents; Spectral behavior also shown corresponding to the current 20 % above threshold.

between the longitudinal modes of the system. One can depict that neutron irradiation can then cause instability or stability to VCSEL, in term of self-pulsations, at certain doses of radiations.

CONCLUSION

From the experimental results it can be concluded that neutron irradiation can alter VCSEL characteristics. It was suggested that VCSELs structure plays an important role in their response to neutron radiation. The slope efficiency and threshold current of VCSELs can be improved or degraded by neutron irradiation, depending on the VCSEL type and radiation dose. However, VCSELs become more sensitive to temperature after irradiations. The L-I characteristics were found to be reversible in one VCSEL device and remained unchanged in other VCSELs. Neutron irradiation may induce extra, or maintain a single, mode in the spectral behavior of VCSELs with certain shifts in the values of the peak emission wavelength. VCSEL were irradiated for more than 100 days with no sign of degradation in characteristics. Self-pulsations in VCSELs' output can be eliminated by fine adjustment of neutron doses. The results presented here showed significant effects of neutron radiation on VCSEL characteristics, however, a wider variety and a large ensemble of VCSELs should be examined to further confirm these conclusions. This presents and interesting field of investigations both from the applications and device characteristics view point.

REFERENCES

Aldwayyan, AS., Al-Qahtani, HR., Alsalhi, M. and Raja, MYA. 2004. Characteristics of GaAs/AlGaAs vertical cavity surface-emitting Lasers irradiated with gamma-rays. J Opt Eng. 43(9): 2184-2192.

Andrieux, ML., Dinkespiler, B., Lundquist, J. and Martin, O. 1999. Neutron and Gamma Irradiation Studies of Packaged VCSEL Emitters for the Optical Read-out of the ATLAS Electromagnetic Calorimeter. Nuclear Instruments and Methods in Physics Research. A 426**.**

Barnes, CE. 1985. Radiation effects on light sources and detectors. Radiation Effects in Optical Materials. SPIE. 541.

Berghmans, F., Van Uffelen, M. and Decreten, M. 2002. Combined Gamma and Neutron Radiation Effects on VCSELs. Proceedings Symposium IEEE/LEOS Benelux Chapter. 71-74.

Beringer, J., Borer, K., Mommsen, RK., Monnier, E., Nickerson, RB., Weidberg, AR., Hou, HQ. and Lear, KL. 1997. Radiation Hardness and Life Time Studies of LEDs and VCSELs for the Optical Readout of ATLAS SCT. ATLAS internal note INDET-NO-183.

Camparo, JC., Delcamp, SB. and Frueholz, RP. 1992. AlGaAs diode Laser blue shift resulting from fast neutron irradiation. J. Appl. Phys. 71 (11).

Gill, K., Arbet-Engels, V., Cervelli, G., Grabit, R., Mommaert, C., Stefanini, G., Vasey, F. and Troska, J. 1998. Pion damage in semiconductor lasers. CMS NOTE 046.

Gill, K., Grabit, R., Persello, M., Stefanini, G., Vasey, F. and Troska, J. 1997. Neutron damage studies of Semiconductor laser for the CMS tracker optical data links. proc. RAECS conf.

Gregor, I., Pearce, M., Dowell, J., Jovanovic, P., Kootz, A., Mahout, G., Mandic, I. and Weidberg, T. 2000. VCSEL – based Custom Radiation Tolerant Optical Data Links. SPIE. 3946:187-195.

Jiang, C., Zhou, G., Xu, J., Den, P. and Gan, F. 2003. Gamma-rays and Excimer laser irradiation effect on YAG crystals. J. Cryst. Growth. 257:301-304.

Joanne Y Law *et al*., 1997. Effects of transverse-mode competition on the injection dynamics of vertical-cavity surface-emitting lasers. Quantum Semiclass. Opt. 9.

Joze Mulet Pol. 2002. Semiconductor Laser Dynamics: Compound – cavity , polarization and transverse modes. PhD thesis. de la Universitat de les Illes Balears. per optar al grau de Doctor en ci`enciesF´ısiques.

Langley, LN. and Shore, KA. 1997. The effect of optical feedback on noise properties of vertical cavity surface emitting lasers. Proc. Inst. Elect. Eng- Optoelectronics. (144):34-38.

Lee, SC., Zhao, YF., Schrimpf, RD., Neifeld, MA. and Galloway, KF. 1999. Comparison of Life Time and Threshold Current Damage Factors for Multi14 Quantum-Well (MQW) GaAs/GaAlAs Laser Diodes Irradiated at Different Proton Energies. IEEE 46(6).

Mommsen, RK. 1997. Life Time Studies of Irradiated LEDs and VCSELs for the ATLAS Experiment at the Large Hadron Collider. diploma thesis. University of Bern.

Raja, MYA., AL-Dwayyan, A., CAO, Y. and Wang, CX. 2000. Polarization Stability and Modal Properties of Packaged Gigabit VCSELs. SPIE Symp. Optical Devices, Components& Systems, OPTO South-East Charlotte NC.

Wilmsen, C., Temkin, H. and Coldren, L.A. 1999. Vertical-Cavity Surface Emitting Lasers. Cambridge University.