

## Combined Gamma and Neutron Radiation Effects on VCSELs

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*Optical fiber technology is seriously considered for applications in various radiation environments, including space, high-energy physics, nuclear power plants and future thermonuclear reactors. The feasibility of applying photonic technology in nuclear radiation fields therefore needs to be assessed. Our recent results of combined gamma and neutron irradiations of vertical-cavity surface-emitting laser (VCSEL) assemblies indicate that at a gamma total dose of 20 MGy, the optical power loss at nominal forward current was less than 2 dB. VCSELs previously exposed to gamma rays exhibited an accelerated degradation under neutron radiation. The beneficial effect of applying a continuous forward bias to the VCSELs is also evidenced.*

### Introduction

Although a considerable amount of radiation effects studies on individual devices, including optical fibers, light-emitting diodes, laser diodes and photodiodes exposed to a variety of radiation conditions is reported in literature, only little information is available on the radiation tolerance at high total ionizing radiation dose (e.g. > 1 MGy) and for a substantial neutron fluence. In this paper we therefore focus on the high dose radiation response of vertical-cavity surface-emitting lasers (VCSEL), which have already proven to exhibit an enhanced radiation tolerance compared to other types of optical emitters, e.g. LEDs [1]. Because of their structure and since they operate under very much different conditions than conventional edge-emitting lasers (EELs), VCSELs are more complex devices compared to EELs in the ways that affect the radiation response [2]. They are nevertheless considered as quite radiation tolerant, with the reticence that due to their non-constant slope efficiency, they can tolerate less particle radiation induced change in threshold voltage than conventional EELs [3]. In addition, VCSELs have proven to be excellent candidates as optical sources for optical communication links in high-energy physics experiments [4].

We first report on the degradation of VCSEL assemblies, exposed to a high total dose (20 MGy) of gamma radiation. Then, we compare the effect of neutrons with a typical moderated fission energy spectrum to that of gamma rays. For the neutron irradiations, we used both pristine pig tailed VCSEL assemblies and components which were previously exposed to the 20 MGy gamma dose. The pre-irradiation seems to affect the response to neutrons. Additionally, we observe the positive effect of continuously forward biasing the VCSELs under neutron irradiation. These devices are indeed known to exhibit forward bias annealing [5].

### Target devices, Experimental set-up and irradiation conditions

The structure of the VCSEL assemblies which were the subject of the gamma irradiation experiments is shown in Fig. 1. The devices were packaged with standard pigtail technology in a metal housing allowing to couple the optical power emitted by

the VCSEL into a 100  $\mu\text{m}$  core SPECTRAN TCG<sup>®</sup>-type pure silica fiber, by means of a 2 mm diameter glass ball lens. The selection of the optical fiber follows from its well-established radiation tolerance [6]. The fiber pigtails are about 1 m long.

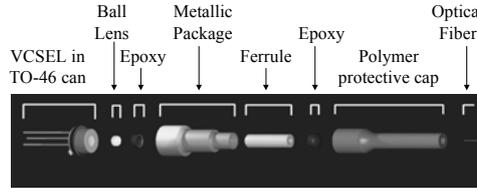


Fig. 1: Exploded view of a pigtailed VCSEL under test, showing the different parts of the assembly.

Fig. 2 depicts the optical power versus forward current  $I_f$  (P-I) curves of the components before irradiation. Assemblies with MITEL VCSELs are labeled from A to D, whereas the assemblies with HONEYWELL devices are numbered from 1 to 4. The fiber-coupled optical power for VCSELs 1 to 4 is lower than for VCSELs A to D, due to the absence of a ball lens. The emission wavelength of all VCSELs lies around 850 nm.

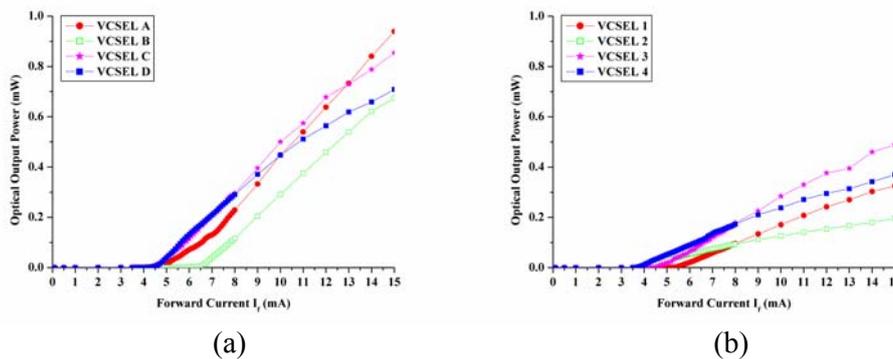


Fig. 2: P-I characteristics of the VCSEL assemblies before irradiation, measured at a temperature of  $60\text{ }^\circ\text{C} \pm 1.5\text{ }^\circ\text{C}$ . (a) MITEL VCSEL assemblies with ball lens. (b) HONEYWELL VCSEL assemblies without ball lens.

The Power – Forward Current – Voltage (P-I-V) curves of the VCSELs were measured on-line, i.e. during the irradiations, at 30 minute intervals. In between these measurements, VCSELs A, B, 1 and 2 were continuously biased with a 12 mA forward current. Devices C, D, 3 and 4 were only exercised during the measurement of their P-I-V curves.

The gamma irradiation was performed in an immersed  $^{60}\text{Co}$  facility at SCK•CEN (Mol, Belgium) at a dose-rate of  $15\text{ kGy}\cdot\text{h}^{-1}[\text{H}_2\text{O}]$ . The temperature was kept constant at  $60.0\text{ }^\circ\text{C} \pm 1.5\text{ }^\circ\text{C}$ . The neutron irradiation was conducted in an experimental channel of the air-cooled graphite-moderated BR1 reactor at SCK•CEN (Mol, Belgium). The energy distribution of the neutrons follows a typical moderated fission spectrum and the total neutron flux reached  $2.36 \times 10^{11}\text{ n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$ . During the neutron irradiation, the background gamma radiation dose-rate reaches  $1.8\text{ kGy}\cdot\text{h}^{-1}[\text{H}_2\text{O}]$ . The temperature in the irradiation container was also kept constant at  $60.0\text{ }^\circ\text{C} \pm 1.5\text{ }^\circ\text{C}$ .

## Experimental results and discussion

Fig. 3 shows the optical output power loss of VCSEL assemblies A to D during two successive gamma irradiations of 10 MGy. In the first irradiation, the loss measured at a 15 mA forward current remains below 1 dB for VCSELs A and B, and below 1.5 dB for VCSELs C and D. The lower induced loss at total dose values above 4 MGy for devices A and B can be ascribed to the continuous forward bias. The temperature variations in

the irradiation container were limited to about  $0.6\text{ }^{\circ}\text{C}$ . Although these changes can be considered to be relatively small, they clearly influence the optical power loss. The origin of this temperature dependency of about  $1\text{ dB}\cdot^{\circ}\text{C}^{-1}$ , is not well understood. Since it is larger than the intrinsic temperature sensitivity of the VCSEL, we tend to believe that it stems from the packaging of this device in the pigtailed assembly. After this first irradiation and recovery period, the VCSEL assemblies were left with no forward bias applied for approximately one week at a constant temperature around  $60\text{ }^{\circ}\text{C}$ . Surprisingly, at the start of the second irradiation, the VCSELs showed an optical power loss which exceeded the value obtained at the end of the first irradiation by approximately 1 dB (see Fig. 3 b). Rather than being further affected by the second irradiation, the VCSELs recover to loss values close to those obtained after the first 10 MGy. This can be ascribed to forward bias annealing and shows the importance of keeping the devices exercised in between radiation exposures. However, packaging effects can not be ruled out and the effect of small temperature variations is again evidenced. No recovery could be evidenced during the first 24 hours after the irradiations and the I-V characteristics remained equally stable. There was no observable change in the threshold current.

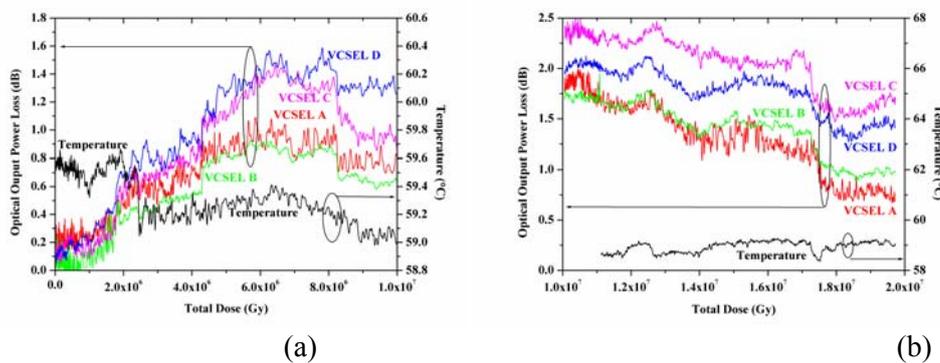


Fig. 3: Optical output power loss for VCSELs A to D.  
 (a) First 10 MGy irradiation. (b) Second 10 MGy irradiation.

Whereas gamma radiation only induces a decrease of the slope efficiency, neutron radiation will also severely affect the threshold current and alter the current-voltage characteristics. The P-I characteristic of VCSEL A for increasing neutron fluence levels is shown in Fig. 4 (similar curves are obtained for all the devices under test). After a neutron fluence of  $3 \times 10^{15}\text{ n}\cdot\text{cm}^{-2}$ , no optical output power could be detected below our maximum test current of 18 mA. The threshold current increased to values beyond the specified nominal forward current of 15 mA which makes the devices unusable at such fluence levels. However, for a neutron fluence below  $10^{15}\text{ n}\cdot\text{cm}^{-2}$ , the VCSELs still operate in an acceptable way.

To compare the response of the different VCSELs to the reactor irradiation, Fig. 5 depicts the optical output power decrease as a function of neutron fluence. The output power changes almost linearly with neutron fluence, as already described in the literature [5]. The threshold current also increases linearly with dose (not shown here) [7]. We can identify four different behaviors, depending on the pre-irradiation and bias conditions. VCSELs B and C, which were pre-irradiated with a 20 MGy gamma dose and which are not continuously biased show the most rapid degradation. On the other hand, VCSELs 1 and 2 which were not gamma pre-irradiated and which are continuously forward biased exhibit the slowest degradation. The gamma pre-irradiation

thus seems to accelerate the decay of the VCSEL characteristics in a neutron radiation field. However, this conclusion needs to be taken with some caution, as VCSELs A to D were obtained from another manufacturer than VCSELs 1 to 4.

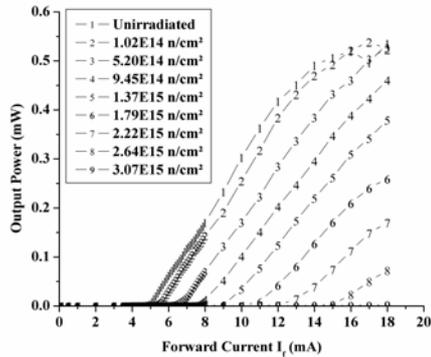


Fig. 4: P-I curves for VCSEL A at different neutron fluence levels and  $60.0\text{ }^{\circ}\text{C} \pm 1.5\text{ }^{\circ}\text{C}$ .

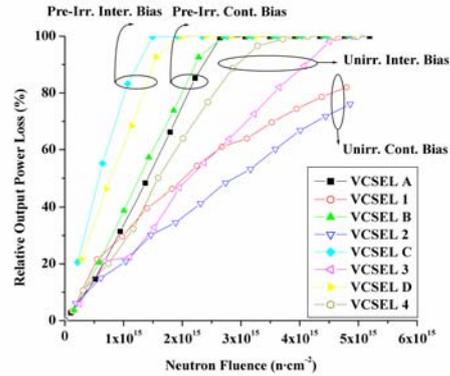


Fig. 5: Relative output power loss as a function of neutron fluence. VCSELs A to D were pre-irradiated with a 20 MGy total gamma dose. VCSELs A, B, 1 and 2 were continuously biased. VCSELs C, D 3 and 4 were only exercised during the measurements.

## Conclusion

We evaluated the operation of commercially available VCSEL assemblies in mixed gamma and neutron radiation fields. The VCSEL assemblies can tolerate an ionizing radiation dose of 20 MGy and possibly above. For neutron radiation, a correct operation can be observed for a moderated fission fluence lower than  $10^{15}\text{ n}\cdot\text{cm}^{-2}$ . This indicates that the VCSELs can be used in very harsh radiation conditions, for example those encountered during maintenance operations of the future ITER International Thermonuclear Experimental Reactor. A gamma pre-irradiation seems to accelerate the degradation observed under neutrons and care should therefore be taken when interpreting the results in mixed radiation fields. The packaging of the VCSELs for use in radiation environments and at higher temperatures remains an issue.

## References

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