Neutron and Gamma Irradiation Studies of Packaged VCSEL Emitters for the Optical Read-out of the ATLAS Electromagnetic Calorimeter

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Abstract

Vertical cavity surface emitting laser diodes (VCSEL's) are being investigated for use in the on-detector transmitters of the ATLAS liquid argon calorimeter optical read-out links. The radiation tolerance of optical components mounted on-detector is a critical concern. Packaged VCSEL emitters from Honeywell and Mitel have been irradiated with neutrons up to $(2.1 \pm 0.4)\times10^{13}$ n (1 MeV equivalent in Si) cm^{-2} and gammas up to (5.1 ± 0.2) kGy. The packaged components were mounted in 'ST' style fibre receptacles and monitored through-out the irradiation. A radiation induced attenuation of 10-15 % was seen after neutron irradiation. The induced attenuation after the gamma irradiation was $<$5 %. The threshold current did not change in either case. An annealing current of between 5 and 8 mA restored the light output levels to pre-irradiation levels after approximately 12 hours for the neutron irradiated devices. The gamma irradiated devices exhibited no such behaviour.

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1 Introduction

The present read-out solution for the ATLAS electromagnetic calorimeter [1] uses approximately 1600 unidirectional Gigabit/s (Gb/s) fibre-optic links to transfer data from front-end electronics boards mounted on-detector to data acquisition electronics situated up to 200 m away. The components at the emitting end of the link will be exposed to high levels of both neutron and gamma radiation. It is essential that the behaviour of these components is well understood under such conditions as access is severely limited once ATLAS is closed and repairs would require a lengthy intervention. Integrated over 10 years of LHC running (and assuming a machine luminosity of 10^{34} cm^2 s^{-1}), the expected doses are : 800 Gy, ionising; and 1.7×10^{13} n (1 MeV equivalent in Si) cm^{-2}. Note that in this paper all fluences are quoted as 1 MeV equivalents in Si and more details of the conversion process are given in section 2. Safety factors of 4 (gamma) and 3 (neutrons) are applied to take into account simulation uncertainties. The receiving part of the link, located off-detector, is not exposed to significant levels of radiation.

The overall architecture of the optical link is still under consideration but VCSEL (Vertical Cavity Surface Emitting Laser) laser diodes are a strong candidate for use at the emitting end of the link. VCSEL's have a number of desirable properties such as high output power (1 mW at 10 mA bias, typically), low threshold currents (typically, a few mA), compatibility with Gb/s data rates, easy and efficient coupling to multimode fibres and low cost as the devices can be tested on wafer. Moreover, it is generally accepted that VCSEL's offer superior radiation tolerance compared to light emitting diodes, mainly due to the smaller junction size. This has been illustrated by several VCSEL irradiation studies performed by groups involved in ATLAS [2], [3]. It should be noted that in all of these studies, prototype (and unpackaged in the case of [3]) components were used. All of the VCSEL studies detailed in this paper use 'off the shelf' packaged VCSEL's.

During the tests described in this paper the VCSEL's were equipped with optical fibres terminated with industry standard ST connectors and monitored through-out the irradiations for changes in light output or threshold current shifts. Some studies were performed of the recovery ('annealing') of damaged components after the irradiation period.

This paper is organised as follows. The next section describes the irradiation facilities and total doses received by the components. An overview of the experimental procedure is given in section 3. This is followed by results in section 4 and there is a summary and discussion in section 5.

2 Irradiation Details

The components were first irradiated with neutrons of mean energy 6 MeV at the SARA facility in Grenoble [4]. The neutrons are produced by impinging 20 MeV deuterons on a beryllium target. The components under irradiation were located approximately 30 cm from the target, behind a cryostat full of liquid argon which was being used for other tests. As with all fast neutron sources, there is some contamination from ionising radiation. As reported in [4] quantifying this contamination is not trivial, but, in terms of induced damage the ionising dose is practically negligible compared to the neutron fluence. The activation of nickel foils was used to determine the absolute neutron fluence to an accuracy of around 15%. The neutron energy spectrum measured at an angle of 0° from the target is shown in figure 1. The technique outlined in [4]

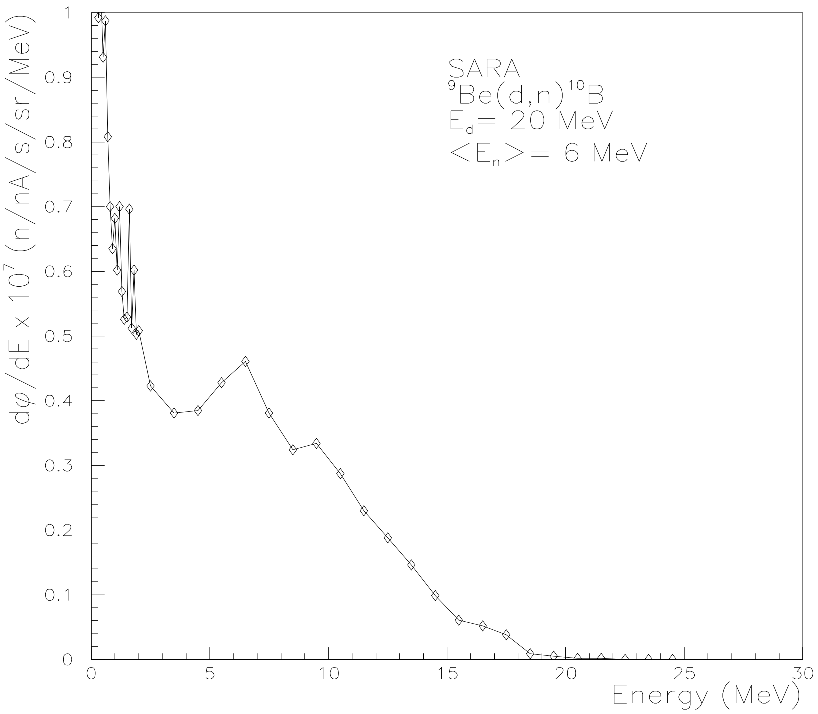

Fig. 1. The neutron energy spectra at SARA measured at an angle of 0° from the target. The detection equipment has a neutron energy threshold of 100 keV. Adapted from [4].

is used to convert fluences into 1 MeV equivalents in silicon using a kerma factor of (2.3±0.3).

The components under test received a total neutron fluence of $(2.10 \pm 0.41) \times 10^{13}$ $\mathrm{n\,(1\ MeV\ Si)\,cm^{-2}}$ in approximately 35 hours. This corresponds well to the fluence expected after 10 years of LHC running, but the instantaneous flux is of course much larger.

The gamma irradiations were performed with a ^{60}Co treatment facility at Karolinska Hospital in Stockholm. As the ^{60}Co source decays it emits two gamma rays at energies of 1.17 MeV and 1.33 MeV. Polymer-alanine dosimeters were used to measure the total ionising dose received by the components under test to an accuracy of around 4%. Solid state detectors were used to cross-check the result. A total dose of (5.1 $\pm$ 0.2) kGy was delivered to the components under test in approximately 70 hours. This corresponds to approximately 65 years of LHC running [2].

3 Test Procedure

Nine Honeywell HFE4080-321 VCSEL's and nine Mitel 1A440 VCSEL's were irradiated with neutron and gamma radiation. The active VCSEL chip is approximately cubic, with sides of approximate length 500 μm. The VCSEL structure is formed from epitaxial layers deposited onto a GaAs substrate. The p-n junction optical cavity is built up from several GaAs quantum layers between AlGaAs barrier layers (so-called quantum wells). All the VCSEL's were housed in TO-46 style packages. The Honeywell VCSEL's were equipped with a plastic lens to enable efficient coupling into an optical fibre. The Mitel VCSEL's had a flat window in place of a lens. The TO-46 package was mounted inside a metal ST package to allow easy connection to optical fibres. The emission wavelength of the VCSEL's is 850 nm.

The VCSEL's were positioned in the radiation beams on two closely spaced FR4 motherboards. Each motherboard contained a mixture of VCSEL types. The Honeywell VCSEL's will be referred to as H1–H9 and the Mitel VCSEL's as M1–M9. The lines of VCSEL's were staggered between motherboards to minimise the amount of material between a given VCSEL and the radiation beam. Measurements were carried out to determine if the light output intensity and/or threshold current of the VCSEL's changed during irradiation. A constant current source was connected through a relay-based demultiplexer system to each VCSEL, the cathodes of which were connected to a common ground. Each VCSEL was connected via an ST connector to an optical fibre. The fibres were packaged as 8-way ribbons terminated with a MT connector. In the counting room, the MT connectors were coupled to a custom 8 channel PIN-diode array which was connected to transimpedance amplifiers. This novel receiver unit is fully described in [5] and was developed as part of a (now abandoned) analogue optical read-out solution for the ATLAS electromagnetic calorimeter [6].

The outputs from the transimpendance amplifiers were connected through a

[2] The length of this test was dictated by access schedules for the irradiation facility.

analogue multiplexer to a 12 bit ADC mounted inside a PC. The current source, demultiplexer, multiplexer and ADC were under the control of the PC which ran LabView software to enable automated testing. The fibres connected to the VCSEL's were routed away from the radiation beams by as shorter path as possible to minimise possible radiation-induced attenuation. Periodically during irradiation (approximately every 20 minutes for the first few hours and then once per hour) the first VCSEL was selected and biased between 0–10 mA in 20 equally spaced steps. At each step, the current was applied for 1 s before an ADC reading was taken. Each ADC measurement consists of 100 samples taken at 1 kHz. When not selected in this way, the VCSEL was connected to a constant bias current. The nominal bias values were 7 mA for H1–H5, 8 mA for H6–H9, 5 mA for M1–M5 and 6 mA for M6–M9. All of these bias currents are above lasing threshold. Approximately 10 minutes was needed to measure all of the VCSEL's in this way.

After irradiation this procedure continued to check for possible annealing effects. After the neutron irradiation, the components were left *in-situ* for 84 hours during these tests. This was not possible after the gamma irradiation but the tests were resumed after a few hours for a period of 90 hours.

4 Results

Figure 2 shows the relative attenuation of the light output from a typical Honeywell VCSEL as a function of the time during neutron irradiation. This plot is typical for each Honeywell VCSEL tested and compatible behaviour is seen for all the Mitel VCSEL's within the timing resolution of the experiment. There is an immediate attenuation of approximately 5-10 % at the start of the irradiation. This is followed by a slight increase in attenuation during the course of the irradiation. At the end of the irradiation, the attenuation level is maintained for approximately 12 hours, after which time an annealing process returns the light output to better than 95 % of the pre-irradiation level.

Figure 3 shows the corresponding results from the gamma irradiation of a typical Mitel VCSEL. As with the neutron irradiation, the Honeywell VCSEL's behaved in the same way. Note that the scatter of the points for the Mitel VCSEL appears smaller than for the Honeywell VCSEL due to the resolution of the ADC and the received power for the Mitel VCSEL's being approximately 10 times smaller than that for the Honeywell VCSEL due the absence of a coupling lens. The attenuation characteristics are noticeably different compared to the neutron irradiation. The attenuation of the light output is proportional to the accumulated dose. The dotted line on the figures indicates the dose expected after 10 years of LHC running and shows an attenuation of $\leq$5 %. After the irradiation there was no evidence for any significant annealing in

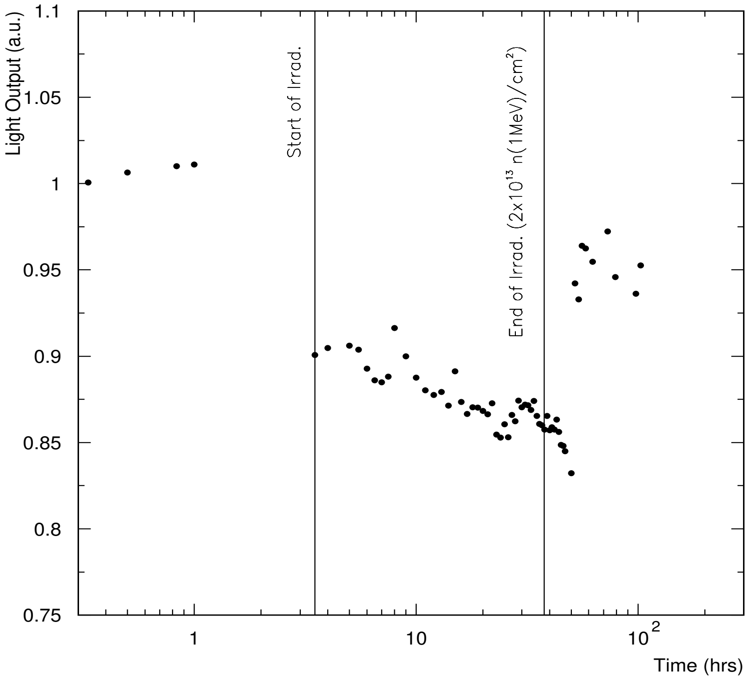

Fig. 2. Relative attenuation of the light output from a typical Honeywell VCSEL as a function of the time during a neutron irradiation. Note the annealing behaviour after the irradiation is completed.

any of the VCSEL's.

The threshold current for either type of VCSEL did not move significantly during either type of irradiation, as shown in figure 4 for a Honeywell VCSEL's during neutron and gamma irradiations. Furthermore, the induced attenuation and annealing behaviour for either brand of VCSEL showed no bias current dependence.

5 Summary and Discussion

Neutron and gamma irradiations have been performed on two brands of commercially available packaged VCSEL laser diodes. The devices from Honeywell incorporated a plastic lens to enhance the fibre coupling efficiency, whereas the Mitel devices had a flat window over the VCSEL's.

During the irradiations, the VCSEL's were biased above threshold with a steady DC current. The light output attenuation for either brand of VCSEL after a 10 year LHC equivalent dose of neutrons (gammas) was 5-10 % (<5 %). During both irradiations, none of the VCSEL's exhibited a change in threshold

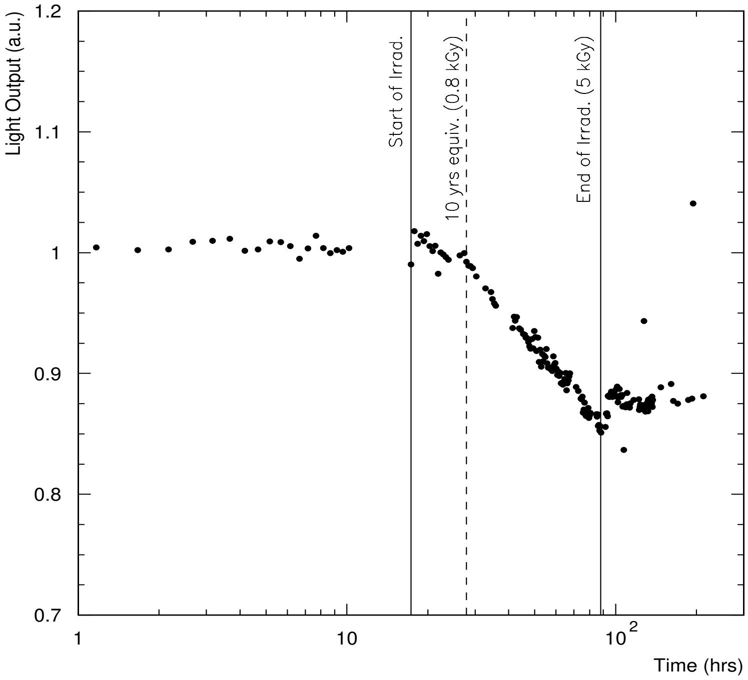

Fig. 3. Relative attenuation of the light output from a typical Mitel VCSEL as a function of the time during a gamma irradiation. Note the absence of annealing after the irradiation is completed. The dotted line denotes a 10 year LHC equivalent dose. The two atypical points seen in the annealing phase are spurious.

current. The light output attenuation observed for the Honeywell VCSEL is consistent with that seen in earlier neutron irradiation studies [2] of a prototype version of this device tested at cryogenic temperatures. After the neutron irradiation the VCSEL's were kept biased and the pre-irradiation light levels were recovered after about 12 hours - no such annealing effect was observed for gamma irradiated VCSEL's biased in a similar manner.

The attenuation in the light output of the VCSEL's is small and will not present a problem for the optical power budgets envisaged for the read-out links of the ATLAS liquid argon calorimeter. A program is now underway to evaluate the radiation resistance of the other components on the transmitting end of the link and in particular the driving electronics.

More generally, VCSEL emitters are increasing in popularity due to their falling cost, desirable optical properties (high output power, low divergence circular beam) and low threshold currents. As VCSEL's also exhibit radiation tolerance they become an attractive proposition for use in hostile environments such as the nuclear industry.

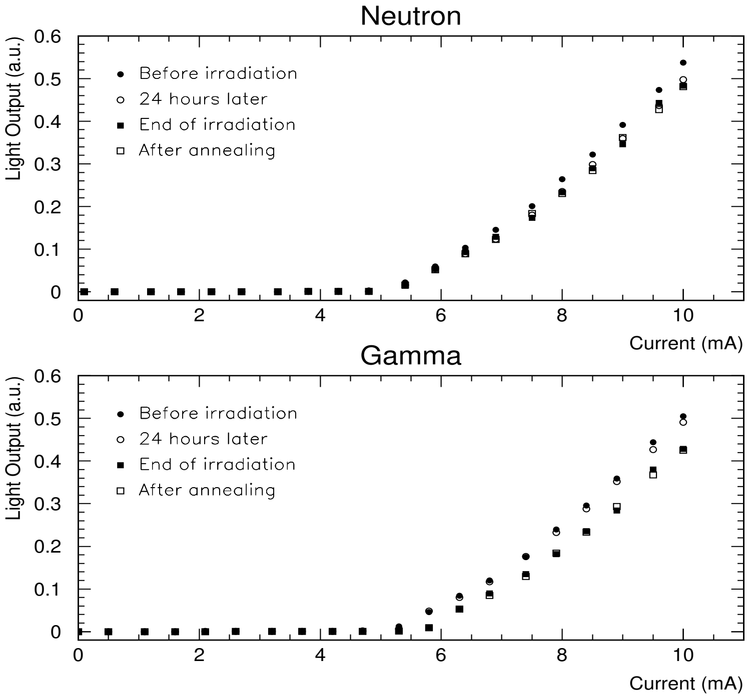

Fig. 4. The output characteristics for Honeywell VCSEL's during neutron and gamma irradiations. In both cases the threshold current does not change. The same behaviour was seen with Mitel VCSEL's.

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