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Irradiation of new optoelectronic components for HL-LHC data transmission links

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ABSTRACT: Candidate optoelectronic components for use in future data-transmission links at the High-Luminosity Large Hadron Collider (HL-LHC) were irradiated with 20 MeV neutrons at the University Cyclotron in Louvain-La-Neuve, Belgium and 24 GeV protons at the CERN PS irradiation facility. The results from this test for multi-channel transmitters, Germanium photodiodes, and Silicon photonics modulators are presented here.

KEYWORDS: Radiation-hard electronics; Front-end electronics for detector readout

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1 Introduction

The upgrade from LHC to High-Luminosity LHC (HL-LHC) will increase the luminosity of the LHC by a factor of 5-10 thus imposing even more stringent requirements on the optoelectronic components used in the front-ends of data-transmission links at the HL-LHC. Not only must they operate in harsher radiation environments, but they must also cope with the increase in data-rates. Components with lower power consumption, higher-speeds, and smaller sizes than those currently used in the optical links installed at the LHC are being investigated as possible candidates for HL-LHC data transmission links. Radiation tests were carried out over the past year on silicon photonics modulators and multichannel transmitters to investigate their tolerance to levels of radiation similar to those expected at the HL-LHC, this paper will present the results of these tests.

2 Optoelectronic components under test

This section will present the devices under test and the procedure used to carry out the irradiation tests on these devices.

2.1 Silicon photonics modulators

Silicon photonics is a new technology approach to modulating light to transfer data at high speeds and with low power over an optical fiber. A silicon photonics optical circuit that could modulate, process and detect light signals could be of interest to HEP applications because of its potentially small size, high speed, low power consumption, and integrability with CMOS electronics and design tools. This is a new technology whose radiation response, to the best of our knowledge, is not known and therefore as a first test of their suitability for HEP applications we looked at the effect of radiation on some Si-based optoelectronic components.

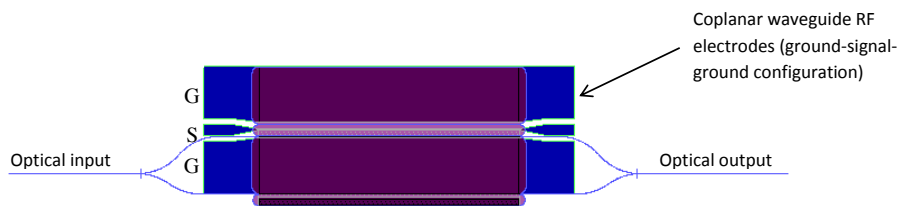


Figure 1: Modulator Layout showing Ground (G) – Signal (S) – Ground (G) configuration. Probe needles are placed on the lower Ground contact and the Signal contact during the DC testing described in this report.

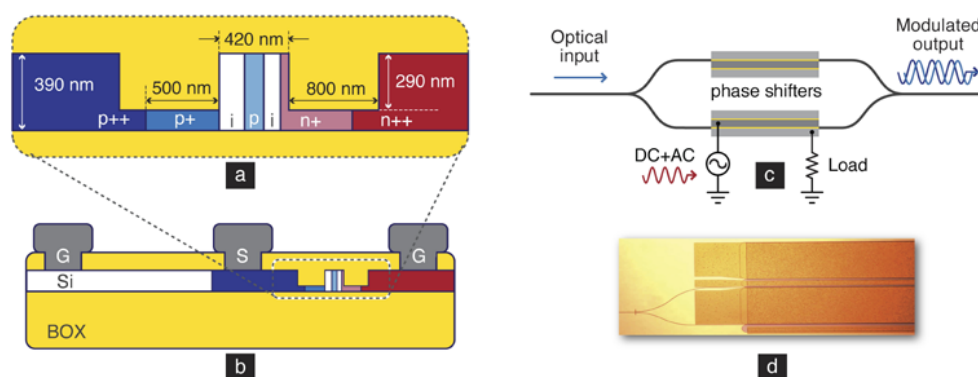


Figure 2: Modulator structure after [3]: (a) the lateral pipin phase shifter, (b) the integration of the phase shifter in coplanar waveguide electrodes, (c): the Mach Zehnder modulator. (d): device picture.

Mach-Zehnder silicon optical modulator samples were provided by Université Paris Sud for the study of their radiation hardness. A schematic of the modulator layout and modulator structure are shown in figure 1 and figure 2 respectively.

Modulation is achieved via the carrier depletion in the active region of the p-i-p-i-n diode structure [1, 2], which is achieved by applying a reverse bias to the junction. Phase modulation is obtained from the change in the effective refractive index of the device induced by the change in carrier densities. To obtain amplitude modulation the waveguides are laid out in a Mach-Zehnder configuration which converts the phase modulation in one branch into an amplitude modulation of light passing through the entire modulator.

Two chips containing 11 Mach-Zehnder silicon optical modulators each were irradiated using the 24GeV proton beam at the CERN PS irradiation facility (IRRAD1). The devices were irradiated over a period of 4 days (3-7 July 2012) with 24GeV protons at an average flux of 3.4×10^9 protons/cm²/s to obtain a total fluence of approximately 1×10^{15} cm⁻². During the irradiation the chips were placed on double-sided kapton tape in the middle of a cut-out made in the 5x5 cm cardboard holders provided by the radiation facility.

Because no optical fibers were coupled to these devices this test will only report on the change

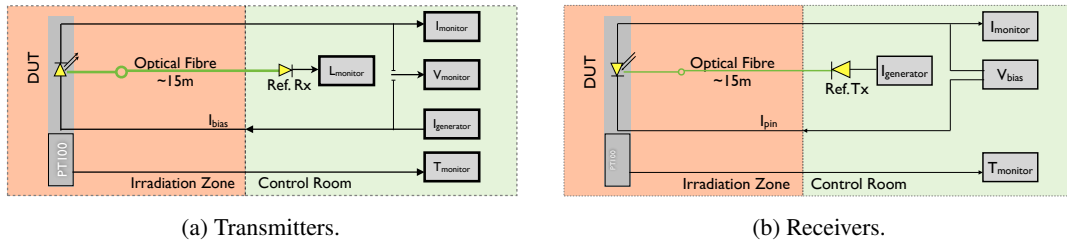


Figure 3: Schematic of irradiation test set-up used at UCL for lasers and photodiodes.

in the DC characteristics of the devices after irradiation. A light-tight probe station was used to measure the forward and reverse IV characteristics of all the modulators on each chip before and 11 days after the end of the irradiation period.

2.2 Transmitters and receivers

The multi-channel transmitters and germanium photodiodes, alongside a range of reference devices including edge-emitting (EELs) and vertical-cavity (VCSELs) lasers and InGaAs photodiodes, were irradiated with 20 MeV neutrons at the University Cyclotron in Louvain-La-Neuve, Belgium. The devices were irradiated for 24 hrs and received a total fluence $\phi = 7.0 \times 10^{15}$ n/cm². This corresponds to a neutron flux which is 3-4 orders of magnitude higher than that expected for tracking detector electronics at the HL-LHC where the total fluence over 10 years of operation is approximately 6×10^{15} n/cm². The static performance of the devices was monitored during the test and their recovery was monitored for 360 hrs after the end of the irradiation period using the set-up shown in figure 3a.

At the start of a measurement cycle the current generator shown in figure 3a was used to increase the bias current (I) applied to the active channel of devices under test (DUTs) from zero to a maximum value in constant increments; the light output (L) and the forward voltage (V) across the DUT were measured at every bias step. The L-I-V curve of the DUT was used to extract the slope efficiency (Eff) and threshold current (I_{th}) of the device.

Two types of multi-channel transmitters were irradiated; a 12 channel InGaAs VCSEL array and a Coarse Wavelength Division Multiplexing VCSEL. The InGaAs laser is a 12-channel array transmitting at 1060 nm with an optical package consisting of a ceramic substrate, a VCSEL array, a micro-lens array and a hardcover with a thin MT-female fiber fixed to the module by a clip. To the best of our knowledge this is the first test carried out on an InGaAs laser in high radiation environments. The other multi-channel transmitter tested was an optical sub-assembly that is capable of transmitting 4 data channels over one multi-mode fiber using Coarse Wavelength Division Multiplexing (CWDM). Such devices are of interest to HL-LHC applications because they could allow an increase in the fiber-bandwidth of the installed link system with no modifications to the currently installed fiber plants.

The germanium photodiodes were also irradiated in the same test, alongside reference InGaAs and GaAs photodiodes, using the set-up shown in figure 3b. Only IV measurements of the germanium devices were possible, there only the change in the dark current of these devices could be monitored during irradiation.

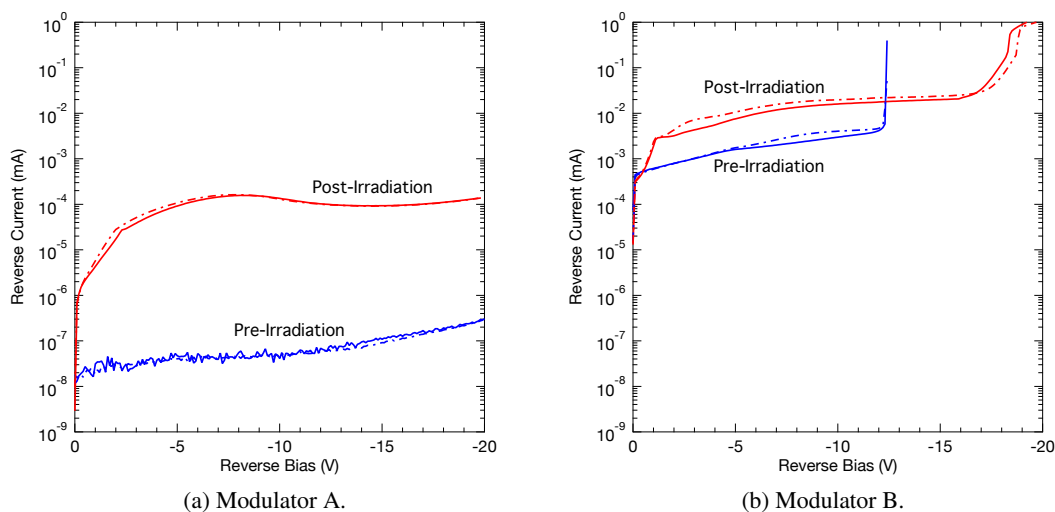


Figure 4: Examples of the effect of protons on reverse bias IV characteristics of modulators of two different structures from the same test chip.

3 Results from radiation tests

3.1 Silicon photonics modulators

The irradiated modulator test chip contained eleven different modulator designs each with slightly different characteristics. The overall effect of the protons on the modulators, shown here in figure 4 for two different modulator structures from the same test chip, was to increase the leakage current in the p-i-p-i-n junction and increase the breakdown voltage of the devices. Exactly how the shape of the IV curve changed after the irradiation varied from device to device, however results were consistent across devices with similar structures from different chips.

Previously X-ray irradiations (to 500kGy) of modulator chips of the same design and fabrication batch were carried out at CERN and showed little change in the I-V characteristics of the devices after irradiation. It was expected, and confirmed by this test, that the particle irradiation, which primarily causes displacement rather than ionization in the target material, would lead to greater changes in the I-V characteristics. Because of the difficulty in extrapolating from the change in the I-V curves the effect of radiation on the modulation properties of these devices, a future test is planned where similar pigtailed devices will be irradiated.

3.2 Multichannel transmitters

The L-I-V curves of three of the twelve channels of the InGaAs VCSEL and all four of the CWDM array's VCSELs were recorded during the neutron irradiation. The typical evolution of the L-I-V curves of a single channel of the InGaAs array and the CWDM VCSEL during irradiation is shown in figure 5. The devices' L-I-V curves show that they behave as expected during the irradiation [4]; as the transmitters are irradiated their slope efficiency decreases and their threshold current increases.

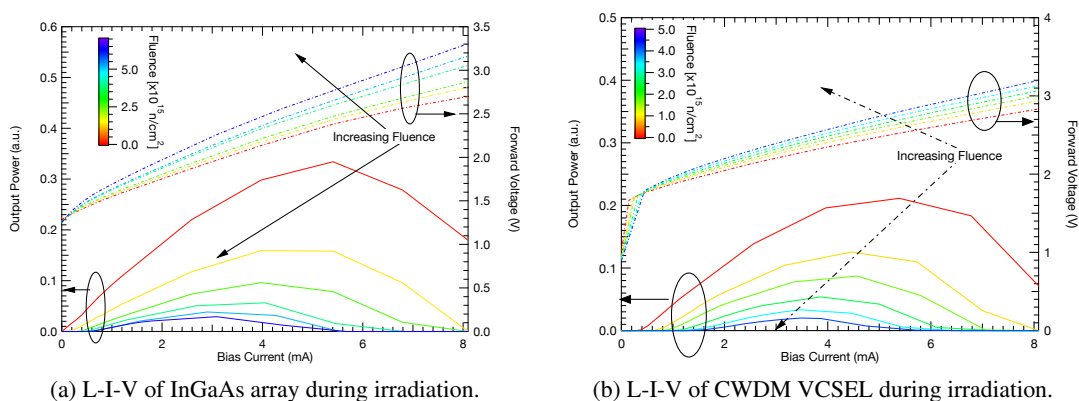


Figure 5: Effect of irradiation on L-I-V of multi-channel transmitters.

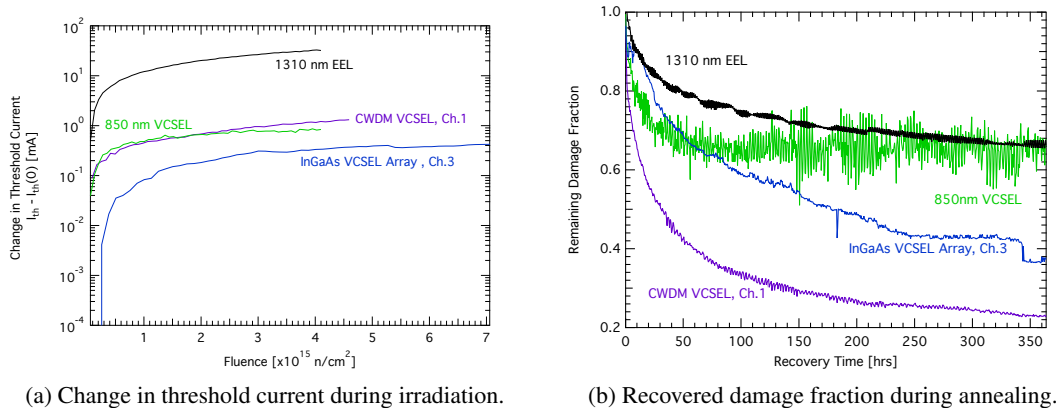


Figure 6: Effect of irradiation on threshold current of multichannel transmitters.

The L-I-V data collected during the test is used to track the changes in threshold current and slope efficiency during the irradiation period (figure 6) and any annealing that might take place after the end of the test (figure 7). Both figures also include results from two reference transmitters, a 1310 nm EEL and an 850 nm VCSEL, irradiated at the same time as the multichannel transmitters and which have been included in previous radiation tests [4].

The increase in the threshold currents (figure 6a) of both the InGaAs array and the CWDM VCSEL is comparable to that observed in the reference short-wavelength VCSELs but their recovery (figure 6b) is faster. One possible explanation for this faster recovery is that the average temperature of the multi-channel devices was higher than that of the single transmitters which can speed up the annealing process. Although the change in threshold current of the devices induced by the particle irradiation is comparable to that observed in other short wavelength VCSELs, figure 7 shows that the observed decrease in the slope efficiency of the multichannel transmitters is almost twice that of the reference VCSELs. Two possible explanations can be put forward for the decrease in the slope efficiency of the multi-channel transmitters: either it was caused by darkening of the passive components in the packaging of the device, or by an increase in the temperature of

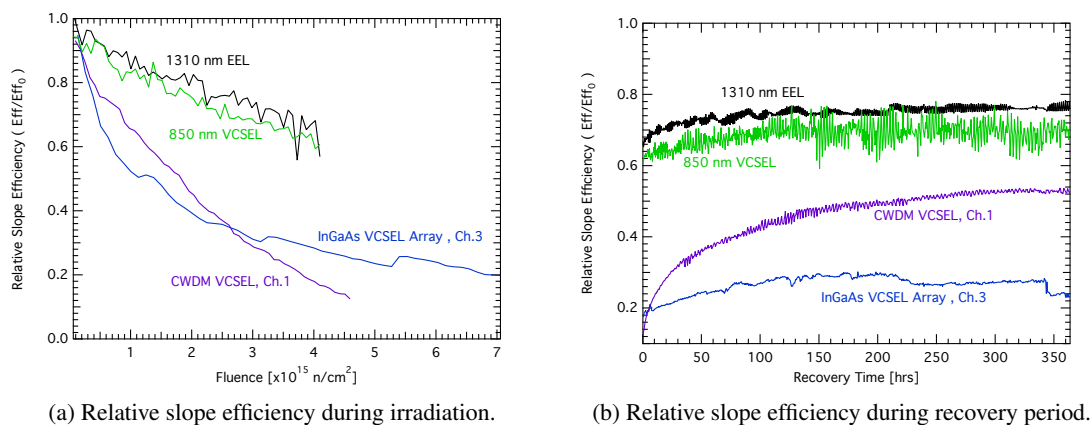


Figure 7: Effect of irradiation on slope efficiency of multichannel transmitters.

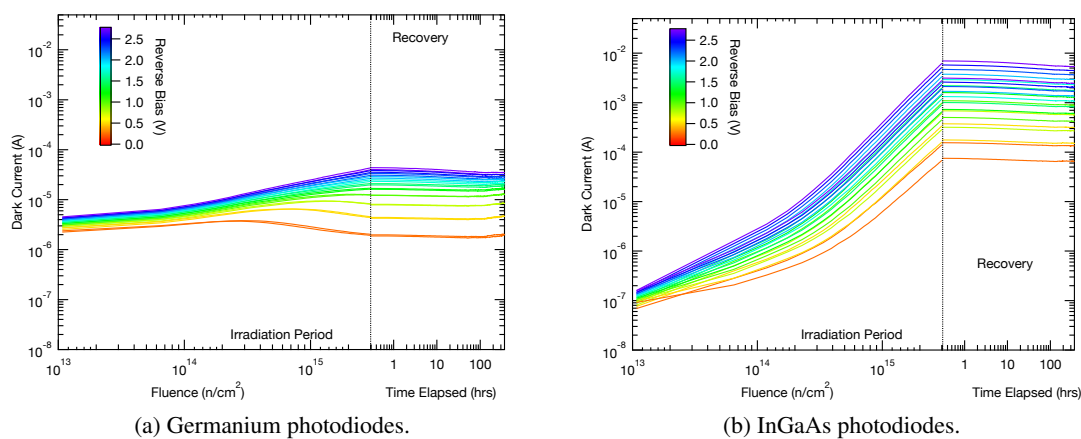


Figure 8: Effect of irradiation on leakage current of photodiodes irradiated at Louvain.

the device due to the increased current densities required to operate the devices after the radiation-induced increase in threshold current. In the case of the CWDM device the latter is suspected due to the strong correlation between the recovery of its threshold current (figure 6b) and slope efficiency (figure 7b) during the annealing period, while for the InGaAs VCSEL array further testing is required to identify the cause and therefore more samples of the InGaAs VCSELs will be irradiated in an upcoming test.

3.3 Germanium photodiodes

Because the irradiated Ge photodiodes were not packaged in such a way as to allow access to the light path of the devices we can only report on the changes in the DC characteristics of the devices.

Figure 8 shows the dark current of the photodiodes during the irradiation period. The leakage current of both the InGaAs and Ge photodiodes increased as the devices were irradiated, although the shapes of the two curves are different. In addition, the leakage current of the Ge diodes was several order of magnitudes smaller than that of its InGaAs counterpart.

4 Conclusions

This paper presents the results from radiation tests conducted on silicon photonics modulators, multichannel transmitters, and germanium photodiodes to investigate their tolerance to levels of radiation similar to those expected at the HL-LHC.

Before and after IV measurements carried out on proton-irradiated MZI modulator samples obtained from Université Paris Sud showed an increase in the leakage current and the breakdown voltage; however no measurements were made on the impact of radiation on the modulating properties of the device. Future tests where pigtailed modulator samples will be irradiated are currently under preparation. In addition to the silicon photonics modulators multichannel transmitters and germanium photodiodes were irradiated to HL-LHC like fluence levels using the 20 MeV neutron irradiation facility at Louvain-la-Neuve. The irradiated multichannel transmitters, a 12-channel InGaAs VCSEL array and a CWDM VCSEL-based device, behaved in a manner similar to a short-wavelength VCSEL irradiated at the same test and were still operational at the end of the test. The radiation induced increase in the dark current of the irradiated Ge photodiodes was smaller than that of InGaAs photodiodes also tested.

Acknowledgments

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