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# Neutron and X-ray irradiation of silicon based Mach-Zehnder modulators

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ABSTRACT: We report on our recent investigation into the potential for using silicon-based Mach-Zehnder modulators in the harshest radiation environments of the High-Luminosity LHC. The effect of ionizing and non-ionizing radiation on the performance of the devices have been investigated using the 20 MeV neutron beam line at the Cyclotron Resource Centre in Louvain-La-Neuve and the X-ray irradiation facility in the CERN PH department. The devices were exposed to a total fluence and ionizing dose of $1.2 \times 10^{15}$ n cm$^{-2}$ and 1.3 MGy respectively.

KEYWORDS: Radiation damage to electronic components; Front-end electronics for detector readout

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## Contents

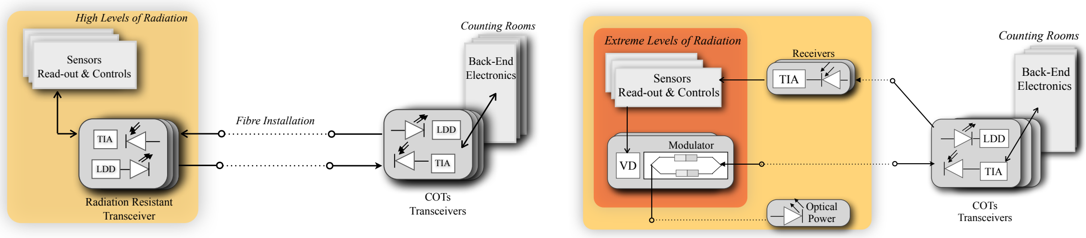


# 1 Introduction

Work has started on identifying new technologies and optical components which could meet the requirements [1] of the High-Luminosity LHC (HL-LHC); an upgrade of approximately an order of magnitude to the luminosity of the LHC planned to take place in 10 years time. The base-line solution for HL-LHC optical links is based on the link architecture used by the Versatile Link [2], but with the on-detector link-component (i.e. the Versatile Transceiver (VTRx)) replaced by a smaller form-factor multi-channel transceiver.

A directly modulated link based on silicon photonics devices, shown in figure 1, is an alternative proposal currently being investigated for upgrade applications where either very high channel densities or extreme radiation-hardness is required. This link design takes advantage of the potential of silicon photonics [3] to produce small, high speed, and low power devices. It also introduces the possibility of moving the optoelectronic components that are known to fail at extreme levels of radiation, i.e. greater than $10^{16}$ n cm$^{-2}$ neutron fluence and a few MGy of total ionizing dose (TID), to regions of the detectors where they can survive the lifetime of the HL-LHC.

The first step in understanding whether this type of link is suitable for HL-LHC applications is to determine the effect of radiation on the silicon photonics devices which would form the on-detector components of such a link. As a first step in this process, Mach-Zehnder silicon modulators designed by the Université Paris Sud and fabricated by ST Microelectronics and CEA-LETI were irradiated in a series of tests carried out in early 2014. The modulators were exposed to levels of radiation comparable to those expected for tracker-type applications after 10 years of HL-LHC operation ($2 \times 10^{15}$ n cm$^{-2}$ fluence, 500 kGy TID).




(a) Versatile link architecture; base-line solution for HL-LHC (b) Directly modulated link

**Figure 1**. Link architectures for HL-LHC data transmission. In the directly modulated links components, which are known to fail in extreme radiation levels, i.e. the transmitter and receiver, are moved to an area of the detector with lower levels of radiation.

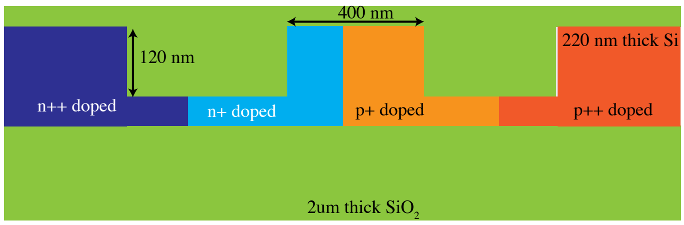



**Figure 2**. Schematic of one arm of the Mach-Zehnder interferometer irradiated in this work consisting of a silicon waveguide in between two layers of $SiO_2$.

## 2 Silicon photonic devices under test

### 2.1 Silicon Mach-Zehnder Interferometers

The modulators [4] irradiated in this work were fabricated on a 300 mm CMOS platform and are based on lateral p-n junctions (figure 2) integrated into a 2.183 mm long Mach-Zehnder interferometer.

Phase modulation in the spectral response of the device results from the change in the effective refractive index of the silicon waveguide induced by the change in carrier densities caused by reverse biasing the p-n junction [7]. By incorporating the phase-shifting diode into the arms of a Mach-Zehnder interferometer the phase modulation of light traveling through the diode is converted to amplitude modulation across the entire modulator.

The phase-shift ($\Delta\phi$) obtained for a given reverse bias can be extracted from the recorded spectral response of the MZI using eq. (2.1)

$$\Delta\phi(V) = 2\pi\frac{\Delta\lambda(V)}{\mathrm{FSR}} \tag{2.1}$$

where $\Delta\lambda$ is the shift in wavelength and the FSR is the free-spectral range of the recorded spectrum. The phase-shift ($\Delta\phi$) achieved for an applied bias voltage will be used in this work as the figure of merit for the optical performance of the devices under test during irradiation. Figure 3 shows an example of how the spectral response of the MZI can be used to extract $\Delta\phi$.



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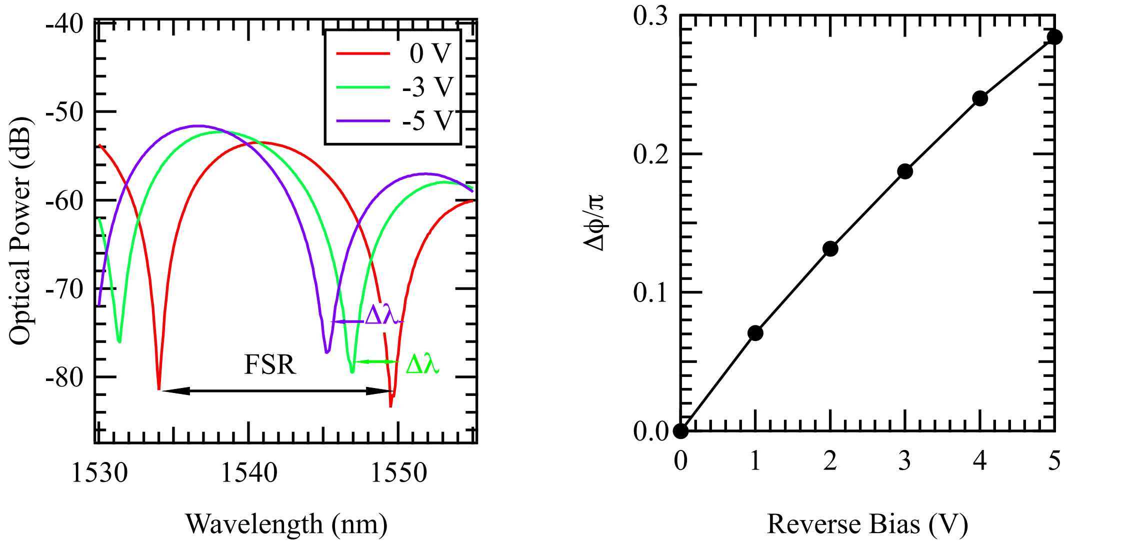


(a) Measured spectrum at output port of an MZI at 0, 3, and 5 V reverse bias

(b) Phase-shift as a function of the applied reverse bias voltage

**Figure 3**. Demonstrating how applying a reverse bias to the phase-shifting diode results in a phase-shift in the transmitted optical signal. The (a) $\Delta\lambda$ and FSR are extracted from the measured optical spectra and used to extract the (b) phase-shift achieved by the device at each reverse bias voltage.

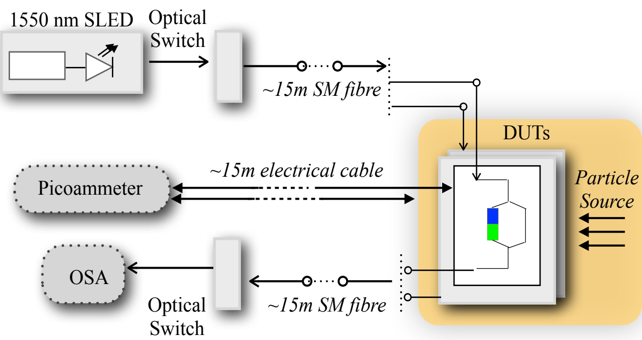


**Figure 4**. Schematic of test set-up used to characterize MZI modulators during the irradiation tests.

## 2.2 Irradiation tests

The high-intensity 20 MeV neutron beam-line at the Cyclotron Resource Centre [5] (CRC) in Louvain-La-Neuve was used to expose two test-chips containing the MZI modulators described above to a neutron fluence of $1.2 \times 10^{15}$ n/cm$^2$ over a period of 16 hours. The effect of ionizing radiation on the modulators was also measured using the X-ray irradiation system [6] at CERN. In that test a single test-chip was exposed to a total ionizing dose of 1.3 MGy in 20 hours. These are radiation levels, in terms of fluence and TID respectively, equivalent to those expected in tracker-type detectors after 10 years of operation at the HL-LHC. Therefore, both tests were highly accelerated tests and a good understanding of the recovery mechanism from both types of damage is required to extend the results to an environment more representative of that expected at the HL-LHC.

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The same experimental set-up, shown here in figure 4, was used to monitor the optical and electrical performance of the devices during both tests. The spectral response of the MZI modulators was recorded using a 1550 nm broadband SLED source and an optical spectrum analyzer (OSA) placed outside the radiation zone. In addition, a picoammeter/voltage source was used to measure the current-voltage characteristic of the devices. The spectral response and reverse current of the devices were recorded for bias voltages between 0 and $-5$ V, in steps of $-1$ V, every 20 min during the irradiation periods. Data-taking continued for 50 hours after the end of the irradiation in order to capture any possible recovery in the DUTs post-irradiation. All measurements were performed with the devices at room temperature.

## 3 Results from radiation tests

This section shows the effect of non-ionizing and ionizing radiation on the electrical and optical performance of the modulators. Results from only one of the two irradiated devices are shown for the neutron test, since the behavior of the two devices tested was identical.

### 3.1 Electrical performance of devices during irradiation

Reverse I-V curves recorded during the neutron and X-ray irradiations are shown in figure 5. The difference in the shapes of the I-V curves obtained during the two tests is due to a light-leak in the measurement set-up during the neutron irradiation. A light-leak affects the measured leakage current because, as described in section 2.1, the DUTs are p-n silicon diodes that can act as photodetectors when illuminated. The fault in the set-up was identified after the neutron irradiation and corrected for all subsequent irradiations.

An increase in the leakage current of the DUTs is observed following both the neutron and X-ray irradiations (figure 5). This was an expected result, as previous work on the effect of radiation on silicon [9, 10] has shown that both non-ionizing and ionizing radiation increase the leakage current of silicon devices. Figure 6 shows that for the radiation levels expected at the HL-LHC the devices' leakage current increases by a few tens of nanoamperes (33 nA and 12 nA for non-ionizing and ionizing radiation respectively). For comparison, the increase in leakage current expected for InGaAs photodiodes used in the on-detector receivers of the optical links currently installed at the LHC is of the order of a few micro-amperes [11].

### 3.2 Optical performance of devices during irradiation

The phase shift, normalized to its pre-irradiation value and obtained at different values of reverse bias, is shown for the duration of the neutron and X-ray tests in figure 7. It clearly shows that ionizing radiation has a much more significant effect on the optical performance of the modulators.

To understand the difference in the behavior of the devices after exposure to these two different types of radiation we need to refer back to the structure of the MZI modulator as described in section. 2, and specifically three aspects of the devices' manufacturing and design. Firstly, it is important to note that the irradiated MZI modulators were fabricated on Silicon-On-Insulator (SOI) wafers with a 2 mm thick buried oxide. Thick buried oxides are used in the manufacturing of silicon photonic devices to improve the confinement of light in the silicon waveguide and reduce the propagation loss in the devices. Secondly, that the n and p doping levels of the diodes used in



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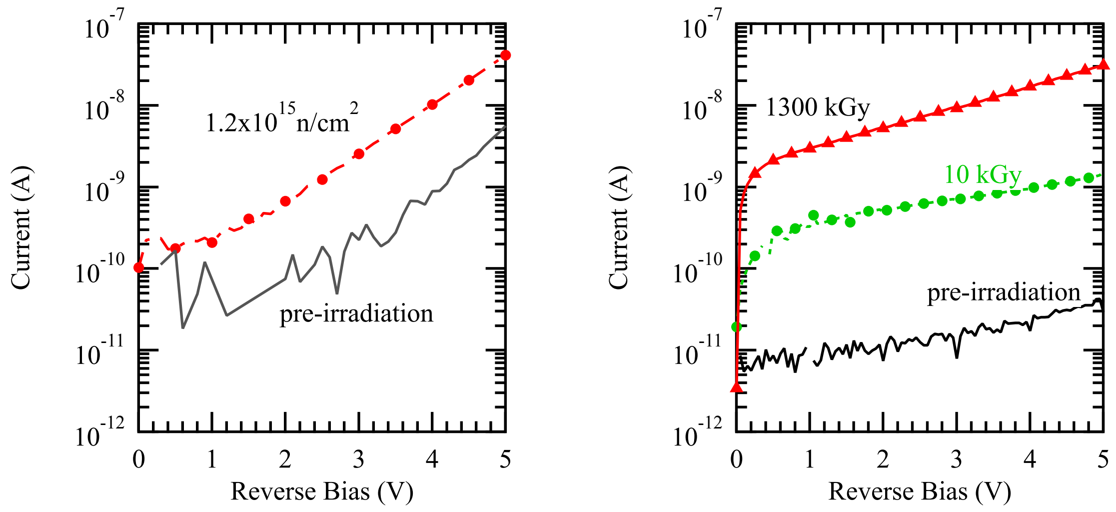
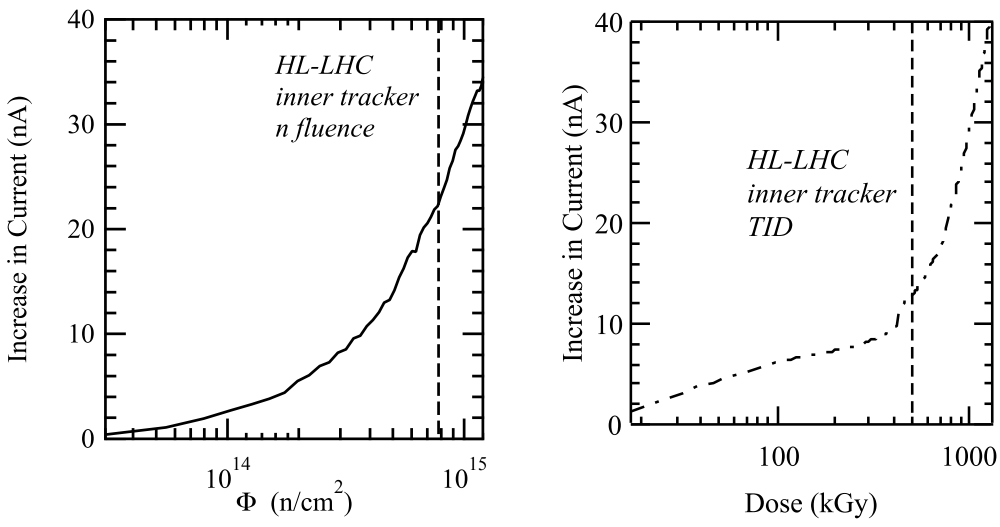



(a) Reverse I-V curves before and immediately after the neutron irradiation. Noise in our measurement set-up due

(b) Reverse I-V curves during X-ray irradiation

**Figure 5**. Effect of (a) non-ionizing and (b) ionizing radiation on reverse I-V characteristic of DUTs. Due to a light leak in the measurement set-up during the neutron test the shapes of the I-V curves obtained during the two tests were different.




(a)

(b)

**Figure 6**. Increase in current at 5 V reverse bias for DUTs during (a) neutron and (b) X-ray irradiation. The reason for the sharp increase in the leakage current after 400 kGy is being investigated.

the arms of the interferometer are on the order of $10^{17}$–$10^{18}$ $cm^{-3}$. High doping levels are used because of the weak dependence of the refractive index of silicon on density of free-carriers [7]. Finally, the location of the p-n junction is chosen carefully to maximize the overlap between the change in free-carriers and the confined optical mode and maximize the phase-shift obtained at a given reverse bias.



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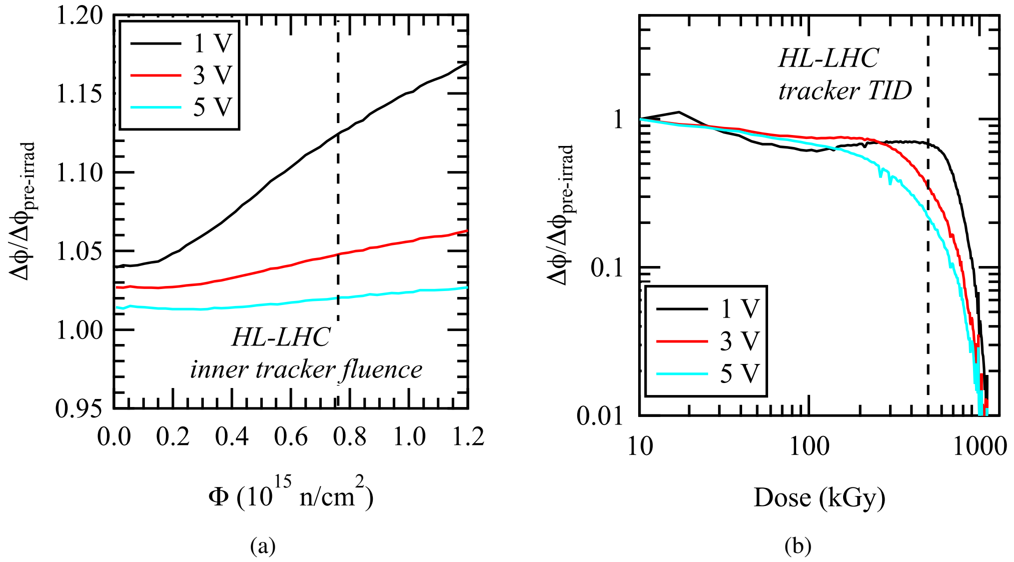


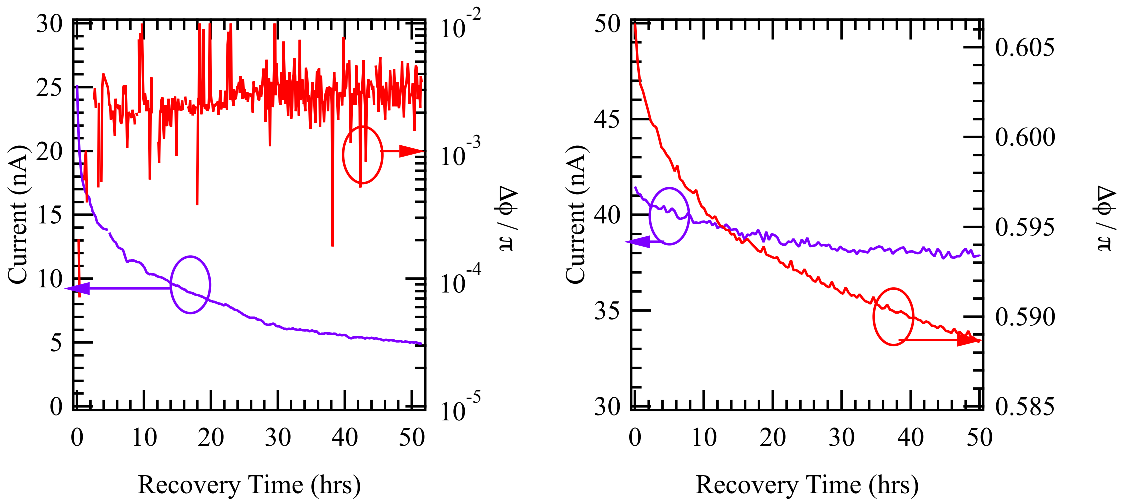

**Figure 7**. Phase-shift, normalized to its pre-irradiation value, during (a) neutron and (b) X-ray irradiation.

We attribute the sensitivity of the devices to ionizing radiation to the presence of the large top and buried oxides in these devices. Ionizing radiation can create both trapped charge and interface traps in the oxide layers of irradiated SOI devices [10]. This can affect the location of free carriers in the silicon waveguide and thereby change the phase-shift achieved for a given applied reverse bias. To explain the devices' relative immunity to non-ionizing radiation we look to the high doping levels used in the phase-shifting diodes. Displacement damage caused by non-ionizing energy loss is known to change the effective doping concentration, and consequently the location of the junction, in silicon detectors [8]. The doping levels in the modulators are much higher than those typically used in silicon detectors ($10^{17}$–$10^{18}$ cm$^{-3}$ rather than $10^{14}$ cm$^{-3}$). Thus, we assume that changes in the effective doping concentrations are very small and therefore changes in the modulation efficiency of the DUTs post-irradiation should also be very small.

### 3.3 Recovery post-irradiation

The reverse current and phase shift measured at an applied reverse bias of 5 V (figure 8) are used to illustrate the behavior of the devices post-irradiation (1.3 MGy total dose and $1.2 \times 10^{15}$ total fluence for the X-ray and neutron results respectively).

A fraction of the radiation-induced damage affecting the leakage current anneals after both tests. This indicates that the increase in the leakage current in the DUTs is dose-rate dependent; therefore, the expected increase in leakage current for a HL-LHC environment will be lower than that measured here. The recovery of the phase-shift is different post X-ray and neutron irradiations; some recovery is measured after the neutron irradiation but almost no recovery is measured post X-ray irradiation. On its own the post X-ray recovery data is not enough to definitively conclude that the modulators cannot recover from the damage accrued from ionizing energy loss. Previous work on the radiation damage to lasers [11] shows that the amount of annealing measured in lasers irradiated in accelerated tests depends on whether the device was still operational at the end of the irradiation. Since the modulators were irradiated until they were no longer operational we




(a) Post X-ray irradiation

(b) Post neutron irradiation

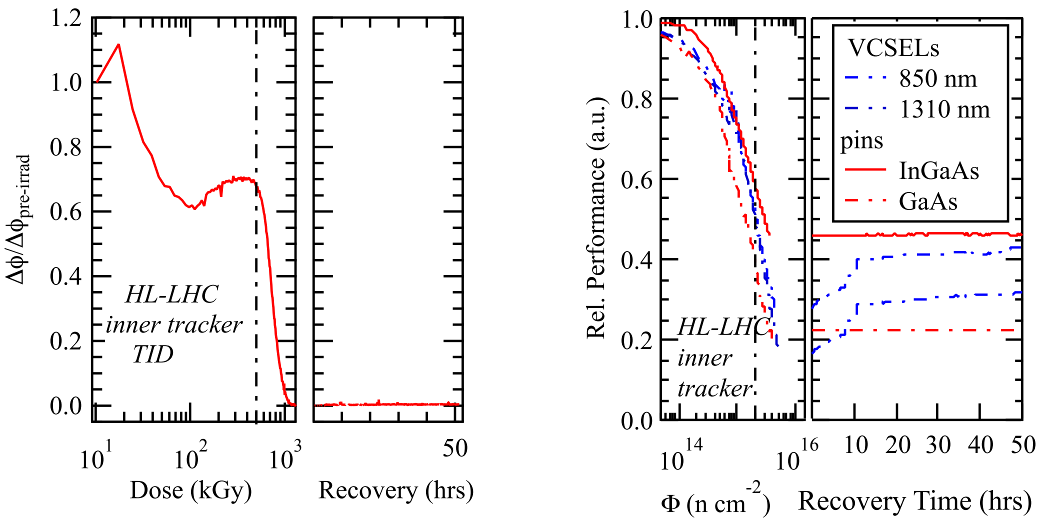
**Figure 8**. Leakage current and phase-shift of a modulator, at an applied reverse bias of 5 V, during the post-irradiation recovery periods of both the (a) X-ray and (b) neutron irradiations.

conclude that more work, for example a low dose-rate test, needs to be performed on the devices to understand the dose-rate dependence of the radiation induced damage in these devices.

## 4 Conclusions

One of the promising new technologies being investigated for HL-LHC data transmission applications is silicon photonics. As a first test of their suitability for HEP environments Si-based optical modulators provided by the Université Paris Sud were exposed to ionizing and non-ionizing radiation using the high-intensity neutron facility at Louvain-la-Neuve and the X-ray irradiation facility at CERN. The devices were exposed to a fluence of $1.2 \times 10^{15}$ n cm$^{-2}$ and a TID of 1.3 MGy. The radiation tests showed that while non-ionizing radiation does not significantly degrade the performance of the modulators they are sensitive to ionizing radiation. The phase-shift obtained at a given bias voltage begins to decrease after exposure to a few hundred kGy of TID, and the device no longer behaves as a modulator after exposure to a MGy of TID.

If these devices are to be considered for use in optical links at the HL-LHC they would have to be at least as radiation resistant as the VCSELs and photodiodes currently used in the on-detector link components. The results from the first radiation tests on the silicon-based devices show this to be true, as shown by figure 9. In it a comparison is made between the change in performance of VCSELs and pin photodiodes irradiated in previous work to that of the modulators. The change in the performance of the VCSELs and pin photodiodes is shown during a neutron irradiation because displacement damage, rather than ionizing damage, is the main damage mechanism affecting their performance in radiation environments [11]. Both the modulators and the VCSELs/photodiodes degrade at the radiation levels expected for tracker-type applications at the HLC, and neither work at the levels expected for even more extreme radiation environments.




(a) Modulators (b) VCSELs and pin photodiodes

**Figure 9**. Evolution of (a) Silicon modulator and (b) VCSELs and pin photodiodes during and after exposure to the most damaging form of radiation for each type of devices (i.e. X-rays for the modulators and 20 MeV neutrons for the III-V devices).

The work presented here demonstrates that silicon photonics is a technology worth investigating for future HL-LHC data transmission applications. Further work is required to complete our understanding of the effects of radiation on these devices, and confirm the observations made from the tests presented here. Another neutron irradiation to a higher total fluence, equivalent to the highest levels expected at the HL-LHC, is planned to confirm our assumption that damage from non-ionizing damage is negligible. In addition, a low dose-rate X-ray irradiation is planned to investigate the dose-rate dependence of the ionizing damage and place a more concrete limit on the maximum level of ionizing radiation that these devices can withstand. Finally, electrical and optical simulations of the devices will be carried out to identify design parameters in the modulators that affect their sensitivity to ionizing radiation.

## References

[1] N. Hessey, *Overview and electronics needs of ATLAS and CMS high luminosity upgrade*, in the proceedings of the *Topical Workshop on Electronics for Particle Physics (TWEPP 2008)*, September 15–19, Naxos, Greece (2008).

[2] L. Amaral et al., *The versatile link, a common project for super-LHC*, 2009 *JINST* **4** P12003.

[3] Z. Fang and C. Zhou Zhao, *Recent progress in silicon photonics: a review*, *ISRN Optics* (2012) 428690.

[4] D. Marris-Morini et. al, *A* 40 *Gbit/s optical link on a 300-mm silicon platform*, *Opt. Expr.* **22** (2014) 6674.

[5] K. Bernier, *Étude du comportement de détecteurs gazeux à micro-pistes MSGC sous irradiation intense de neutrons rapides*, Ph.D. thesis, Université catholique de Louvain, Louvain, Belgium (2001).

[6] *X-ray irradiation system at CERN*, http://proj-xraymic.web.cern.ch/proj-xraymic/.

[7] R.A. Soref, *Electrooptical effects in silicon*, *IEEE J. Quant. Electron.* **23** (1987) 123.

[8] G. Lindstrom, *Radiation damage in silicon detectors*, *Nucl. Instrum. Meth.* **A 512** (2003) 30.

[9] M. Moll, E. Fretwurst and G. Lindstrom, *Leakage current of hadron irradiated silicon detectors – Material dependence*, *Nucl. Instrum. Meth.* **A 426** (1998) 87.

[10] H.J. Barnaby, *Total-ionizing-dose effects in modern CMOS technologies*, *IEEE Trans. Nucl. Sci.* **53** (2006) 3103.

[11] J. Troska et. al, *Radiation damage studies of lasers and photodiodes for use in multi-Gb/s optical data links*, *IEEE Trans. Nucl. Sci.* **58** (2011) 3103.