Test of InP-based Mach Zehnder modulator for radiation hardness

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High Energy Physics experiments at CERN in the Large Hadron Collider for example, employ a plethora of mixed-signal integrated circuits to detect particles. Digital read-out architectures of such particle detector circuits are complex and demand high speed serial links. Detector circuits demand data rates of multiple Gbps per chip and several Tbps for the whole detector and this demand is ever increasing as experiments progress to higher luminosities. Possible solution to tackle the problem of high data rates is to transport data optically by external modulation of a continuous wave laser.

The detector circuits have to operate in a high radiation environment and particles passing through the circuits alter the properties of the circuits giving rise to performance issues.

In this work, we investigate the radiation hardness performance of InP-based Mach-Zehnder modulators. The modulator circuit is mounted on a small PCB and irradiated with a 24 GeV/c proton beam at CERN up to various fluencies. The irradiated samples are then characterized and compared against measurements of non-irradiated devices.

Introduction

High Energy Particle Physics (HEP) experiments at CERN in the Large Hadron Collider for example, collide particles (protons or heavy ions) against each other and employ a wide range of detectors to detect particles that originate out of the interaction. These detectors are comprised of various sensor elements and electronic circuits to read out the sensors. Digital read-out architectures of such particle detector circuits are complex and demand high speed serial links to send enormous amounts of data to a computer farm. This demand for bandwidth is ever increasing as experiments progress to higher luminosities. Detector circuits demand serial data rates in multiple Gbps per chip and several Tbps for the whole detector. Copper co-axial cables combined with CMOS technologies are seen reaching their limits at data rates of 10 Gbps for a couple of meters of cable. Possible solution to tackle the problem of high data rates is to transport data optically.

The detector circuits have to operate in a high radiation environment [1]. Particles passing through the circuits causes trapping of charges at interfaces, cause damage to crystal structure etc giving rise to performance issues. State of the art techniques include reading out the data on electrical links for the first couple of meters. At this stage, the data is transmitted optically by directly modulating a Laser diode on to a fiber. The photo-detectors are placed in the computer farm about hundred meters away to read the optical data. The radiation levels are orders of magnitude lower already at a distance of couple of meters. With data rates going high, even these relatively short distance electrical connections are becoming a significant challenge. Performance of Lasers degrade significantly already at less severe radiation environments [2]. Hence, Lasers cannot be modulated directly in this extreme environment. External modulation of a continuous wave laser beam is an alternative solution worth considering, since it doesn't involve active light emitting devices. Such modulator devices could be placed in high radiation environments, with photo-detectors placed in a far away low radiation environment.

The challenge is to design an Application Specific Photonic Integrated Circuit (ASPIC) that is suitable for HEP applications. For e.g. a Continuous Wave (CW) laser beam is injected in the optical fiber that arrives inside the particle detector area. The CW is modulated in an optical phase modulator circuit (Mach-Zehnder Modulator) by the digital read out chip. The modulated laser light is sent on a return optical fiber outside the particle detector area for data acquisition and processing. The CW laser, the photodiode and further processing electronics can be housed in the low-radiation environment i.e. outside the particle detector area. (Fig. 1)

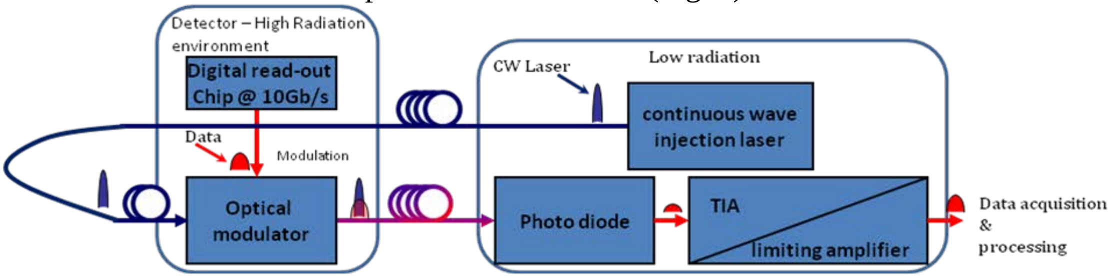

Fig. 1: Block diagram depicting radiation environments and external modulation.

However, Radiation hardness performance of aforementioned circuits is not investigated as of yet.

Challenges foreseen in this solution:

1. To investigate and understand the radiation hardness performance of existing modulator circuits.
2. To build a radiation-hard ASPIC with components like modulators, Arrayed Waveguide Gratings etc.

Irradiation Tests

Much literature is available on radiation hardness of $LiNbO_3$ devices [3], while little is known on III-V semiconductor based devices. Multiple Quantum Well (MQW) devices perform better than bulk devices under irradiation [4]-[7]. The motivation behind the tests is to characterize and understand the behaviour of MQW Mach-Zehnder Modulators (MZMs) in InP technology under proton beam irradiation. Oclaro kindly supplied a number of MZMs in bar form. Each bar consists of 22 modulator structures, based on active-P MQW on N doped InP substrate technology. Four such bars were exposed to 10^{12} p/cm^2 (protons/cm^2), 10^{13} p/cm^2, 10^{14} p/cm^2 and 10^{15} p/cm^2 fluence (1 MeV neutron$_{equivalent}$) respectively. These devices are compared in performance against a non-irradiated device. Also, circuits need to be biased under irradiation to define as in realistic operating conditions. The samples are tested in IRRAD-1 facility at CERN PS East Hall where samples can be exposed to 24 GeV/c proton beam (area ~ 2×2 cm^2) and reach fluencies of 1 – 3×10^{13} p/cm^2 per hour. A shuttle is used to move in an out of the beam. The shuttle can hold multiple samples at the same time. (Ref. https://irradiation.web.cern.ch/irradiation/irrad1.htm)

Design of Printed Circuit Boards

The shuttle used for irradiation can hold samples of size 5×5 cm^2 only. Materials might get radioactive when exposed to irradiation. So, it is preferred to minimize the amount of material. As said before, circuits need to be also biased to mimic realistic operating conditions. Hence, to irradiate the modulators, a very small and thin PCB sub-mount is required (Fig. 2). Since the coupling of a fiber to the waveguide on the device demands some clearance, a pedestal was first glued using conductive glue to the PCB. The modulator bar was then glued on the pedestal. Gold wires of 17 microns were then used to connect to the bond-pads on the PCB (Fig. 3). The dimensions of the sub-mount are 4.8×4.2 cm^2 and it is 0.77 mm thick. In order to minimize the amount of metal, care was taken to use copper only when necessary. The traces are impedance matched and differential in nature. High speed mated 52-pin SAMTEC connectors were used to connect the sub-mount board to the mother-board. The mother board is 18×15 cm^2 in dimensions and 1.6 mm thick. The mother-board houses all the RF connections (Fig. 2). The traces carrying the RF signals were impedance matched and routed differentially. The dielectrics of PCBs are made of normal FR4 material. Due to space constraints, only 11 out of 22 modulators in each bar have been bonded. The cardboard box housing the sub-mount PCB with mounted MZMs is shown in Fig.3 ready to be irradiated. Finally, the whole set-up is loaded in the shuttle as shown in Fig. 4.

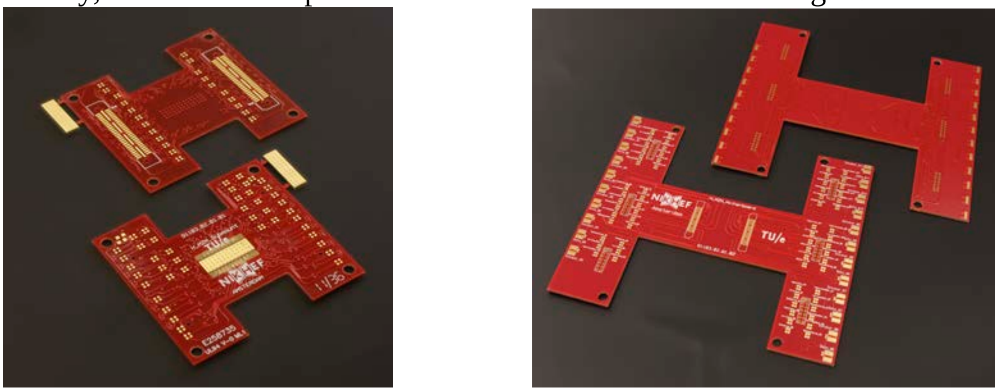

Fig. 2: (L) Unassembled Sub-mount with break-away pedestal. (R)Unassembled Mother-board to house RF connections and also the sub-mount.

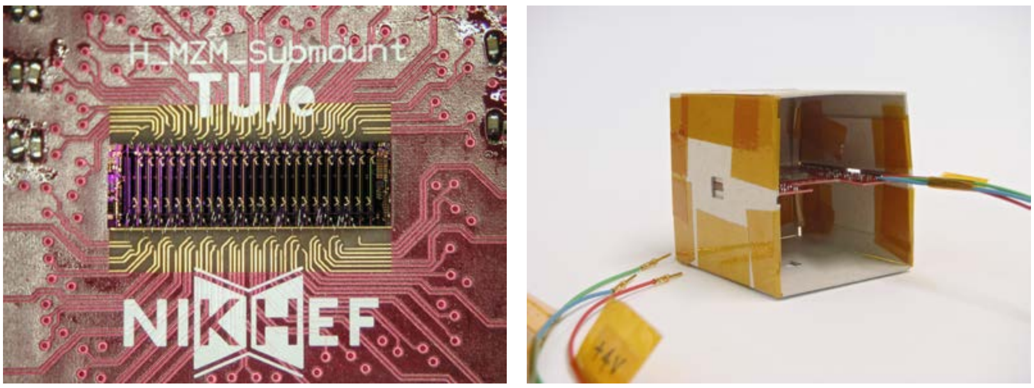

Fig. 3: (L) Modulator bar glued on the pedestal and bonded. (R) Sub-mount PCB housed in a 5×5×5 cm^3 box for irradiation.

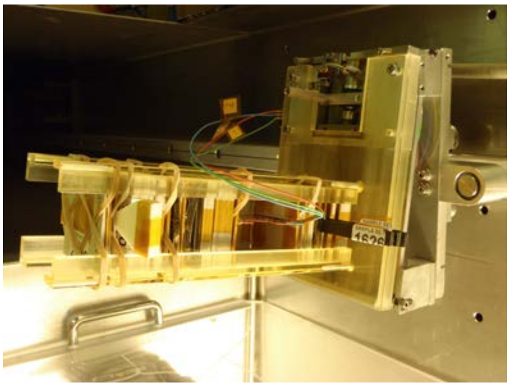

Fig. 4: Sub-mount PCB in the card-board box – loaded in the shuttle for irradiation.

Conclusions and Future

First irradiation tests at mentioned doses were carried out at CERN successfully. The irradiated samples are awaited after careful precautions are taken regarding radioactive material handling. Optical measurements on the non-irradiated modulators are being made at the time of writing this article. Typical measurements include: Measuring phase vs. Voltage characteristics, determining extinction ratio etc. Future steps include analyzing the results of characterisation and understanding the radiation hardness performance of the modulator. Based on the investigation, a modulator will be designed and tested for radiation hardness.

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