Radiation-Hard Optical Link for SLHC

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Abstract

We study the feasibility of fabricating an optical link for the SLHC ATLAS silicon tracker based on the current pixel optical link architecture. The electrical signals between the current pixel modules and the optical modules are transmitted via micro-twisted cables. The optical signals between the optical modules and the data acquisition system are transmitted via rad-hard SIMM fibres spliced to rad-tolerant GRIN fibres. The link has several nice features. We have measured the bandwidths of the transmission lines and the results indicate that the micro twisted-pair cables can transmit signals up to ~ 1 Gb/s. The fusion spliced fibre ribbon can transmit signals up to ~ 2 Gb/s as reported in the previous conference. We have irradiated VCSEL arrays with 24 GeV protons and find four types of VCSEL arrays from three vendors survive to the SLHC dosage. We have also demonstrated the feasibility of fabricating a novel opto-pack for housing VCSEL and PIN arrays with BeO as the substrate.

I. INTRODUCTION

The SLHC is designed to increase the luminosity of the LHC by a factor of ten to 10^{35} $cm^{-2}s^{-1}$. Accordingly, the radiation level at the detector is expected to increase by a similar factor. The increased data rate and radiation level will pose new challenges for a tracker situated close to the interaction region. The present optical link [1] of the ATLAS pixel detector [2] is mounted on a patch panel instead of directly on a pixel module. This separation greatly reduces the radiation level at the optical modules (opto-boards) and simplifies the design and production of both the pixel modules and opto-boards. Data communication between the separated modules is achieved by transmitting electrical signals using ~ 1 m of micro twisted-pair cables. The optical signals between each opto-board and the off-detector optical electronics are then transmitted via 8 m of rad-hard/low bandwidth SIMM fibre ribbon fusion spliced to 70 m of rad-tolerant/medium bandwidth GRIN fibre ribbon. The optical signals are generated and received using the VCSEL and PIN arrays, respectively. We currently transmit optical signals at 80 Mb/s and expect to transmit signals at 1 Gb/s for the SLHC. If the present architecture can transmit signals at the higher speed, the constraint of requiring no extra service space is automatically satisfied.

We have started an R&D program to study the feasibility of an upgrade based on the optical link architecture of the current pixel detector while taking advantage of the several years of R&D effort and production experience. In this paper, we present results on the bandwidth measurement of micro twisted-pair cables and the radiation hardness of VCSEL arrays. In addition, we report the results on a novel opto-pack for housing VCSEL and PIN arrays fabricated with BeO as the substrate. The bandwidth of a fusion spliced SIMM/GRIN fibre ribbon and the radiation hardness of silicon PIN arrays have been reported in the previous conference [3].

II. BANDWIDTH OF MICRO TWISTED-PAIR CABLES

Commercial copper cables [4] can transmit several Gb/s over tens of meters. However, the diameters of these cables are too large for the pixel detector. The present pixel optical link uses a micro twisted-pair of wires for transmission of low voltage differential signals (LVDS) between a pixel module and the driver and receiver chips on an opto-board. Each pair of wires is twisted 5 turns per inch (TPI) which corresponds to 2 turns per cm. For barrel pixel detectors, each wire is aluminium with a diameter of 100 μm (38 AWG) plus 25 μm of insulation, for an outer diameter of 150 μm. The length of the twisted pairs varies from 81 to 142 cm. The wires for the endcap pixel detector are finer, 60 μm with 12 μm of insulation. The length of these copper twisted pairs is ~80 cm. The impedance of the twisted pairs is ~ 75 Ω.

We have measured the bandwidths of micro twisted-pairs of various lengths, diameters, and numbers of turns per cm [5]. We transmitted LVDS pseudo-random data in the selected cable and measured the signal characteristics at the termination with a LeCroy WaveMASTER 8600A (6 GHz) oscilloscope and differential probe (7.5 GHz). The rise and fall times of the cables are shown in Figs. 1 and 2. The thickest cable tested with 25 μm of insulation and 2 turns/cm has the fastest rise and fall times. However, the current barrel cable which is slightly thinner has similar performance.

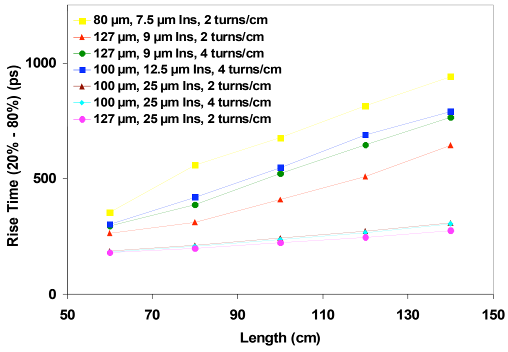

Figure 1: The rise times (20-80%) of the micro twisted-pairs vs. wire length for wires of various diameters and turns per cm.

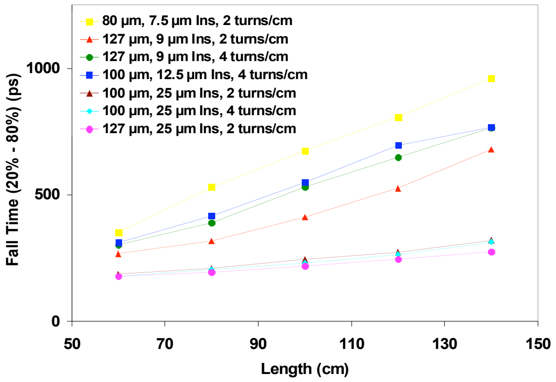

Figure 2: The fall times (20-80%) of the micro twisted-pairs vs. wire length for wires of various diameters and turns per cm.

The eye diagrams produced by transmitting pseudo-random data of 640 Mb/s and 1,280 Mb/s in the current barrel cable and the thicker cable are shown in Fig. 3. The masks shown are adapted from Fig. 39-5 and Table 39-4 of the Gigabit Ethernet Specification (IEEE Standard 802.3) with the mask voltage levels modified to match the LVDS receiver chip used. From these figures, it is evident that the micro-twisted cables are adequate for transmitting signals at 640 Mb/s and that transmission at 1,280 Mb/s might be acceptable. The thicker cable has a slightly higher bandwidth with the slightly more open eye diagrams.

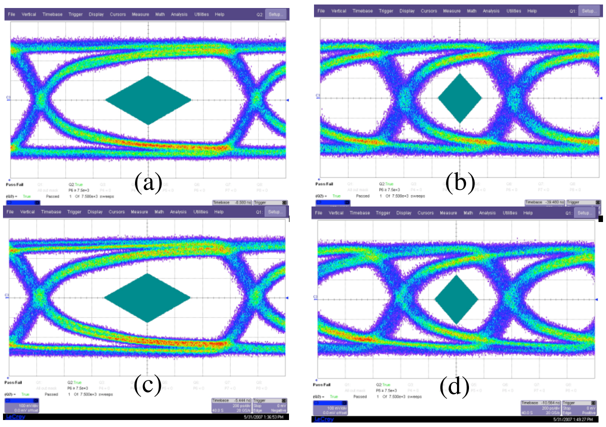

Figure 3: Eye diagrams for signals of (a) 640 and (b) 1,280 Mb/s for the 127 µm cable of 1.4 m with 25 µm of insulation and 2 turns/cm. (c,d) show the corresponding signals for the pixel barrel cable.

III. RADIATION HARDNESS OF VCSEL ARRAYS

We use the Non Ionizing Energy Loss (NIEL) scaling hypothesis to estimate the SLHC fluences [6-8] at the present pixel optical link location (PP0). The estimate is based on the assumption that the main radiation effect is bulk damage in the VCSEL and PIN with the displacement of atoms. After five years of operation at the SLHC (3,000 fb^{-1}), we expect the silicon component (PIN) to be exposed to a maximum total fluence of 1.5 x 10^{15} 1-MeV n_{eq}/cm^2 [9]. The corresponding fluence for a GaAs component (VCSEL) is 8.2 x 10^{15} 1-MeV n_{eq}/cm^2. We study the response of the optical link to a high dose of 24 GeV protons. The expected equivalent fluences at LHC are 2.6 and 1.6 x 10^{15} p/cm^2, respectively. For simplicity, we present the results from the irradiations with dosage expressed in Mrad using the conversion factor, 1 Mrad = 3.75 x 10^{13} p/cm^2 for silicon and 4.57 x 10^{13} p/cm^2 for GaAs. The expected dosages are therefore 69 and 34 Mrad, respectively.

We irradiated opto-boards instrumented with one silicon PIN and two GaAs VCSEL arrays from various vendors using 24 GeV protons at CERN. The PIN and VCSEL arrays coupled to radiation-hard ASICs produced for the current pixel optical link, the DORIC (Digital Opto Receiver Integrated Circuit) and VDC (VCSEL Driver Chip). Furthermore, the opto-boards were mounted on a shuttle system which enabled us to easily move in and out of the beam for annealing of the VCSEL arrays.

We characterized the LIV (Light-Current-Voltage) curves of the VCSEL arrays before the irradiation. In 2006, we irradiated the arrays fabricated by three vendors, Optowell, Advanced Optical Components (AOC, 2.5 Gb/s), and ULM Photonics (two varieties, 5 and 10 Gb/s) [3]. All arrays produced large optical power, in excess of 1 mW for the VCSEL current of 7 mA, the rated maximum current of the ULM 10 Gb/s array. This latter array also required higher voltage, ~ 2.3 V, to produce this current. The 5 Gb/s array required somewhat lower voltage to produce this current and the arrays from the AOC and Optowell, required significantly lower voltage. The latter arrays are therefore more suitable for operation at the SLHC because we expect to fabricate the driver and receiver chips using the 0.13 µm process with a thick oxide option which has a maximum operating voltage of 2.5 V. Given that it requires ~ 0.2 V to operate the transistors in the driver chip, the maximum drive current in the ULM arrays is therefore ~ 7 mA. This implies a lower optical power and less efficient annealing of arrays with radiation damage. In 2007, the AOC 2.5 Gb/s arrays were replace by two new devices operating with higher speed, 5 and 10 Gb/s. Figure 4 shows the LIV curves of the these arrays. These arrays produced large optical power and the required forward voltage to produce 7 mA is significantly less than 2.5 V and hence is suitable for operation at SLHC.

The test system monitored various parameters of the opto-boards throughout the irradiation. Of particular interest was the optical power of the VCSEL arrays vs. dosage. In the 2006 irradiation, we found the optical power of the AOC 2.5 Gb/s and ULM 5 Gb/s VCSEL arrays decreased to zero before the SLHC dosage [3]. Fortunately, we were able to anneal the VCSEL back to continue to produce optical power. We believe that the VCSEL arrays would have performed better should we used a less intense beam and allowed more time for annealing. This is the program we followed in the 2007 irradiation. Figures 5-7 show the optical power vs. dosage for the various arrays. The power decreased during the irradiation as expected. We annealed the arrays by moving the opto-boards out of the beam and passing the maximum allowable current (~ 10 mA per channel) through the arrays for several hours each day. The optical power increased during the annealing. However, there was insufficient time for a complete annealing. All devices continued to produce good optical power up to the SLHC dosage of 34 Mrad, except ULM 5 Gb/s which was least radiation-hard, consistent with the observation of 2006.

We also irradiated GaAs VCSEL arrays by AOC, Optowell and ULM and are awaiting the return of the devices to the home institution for further analysis after the radiation cool down.

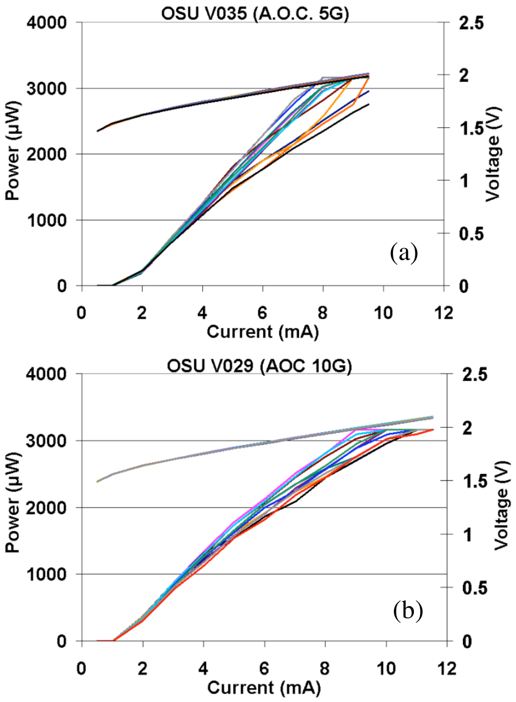

Figure 4: LIV curves of the (a) 5 and (b) 10 Gb/s VCSEL arrays by AOC before irradiation.

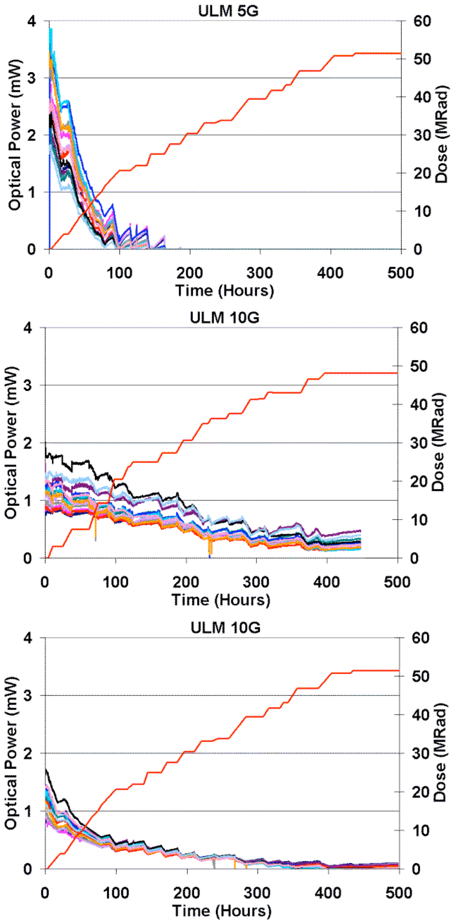

Figure 5: Optical power as a function of time (dosage) for the ULM VCSEL arrays that transmitted data to the control room. The power decreased during the irradiation but increased during the annealing as expected.

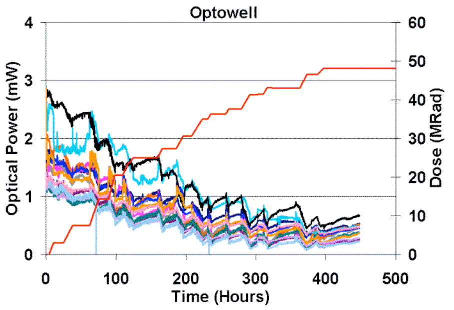

Figure 6: Optical power as a function of time (dosage) for the Optowell VCSEL arrays that transmitted data to the control room. The power decreased during the irradiation but increased during the annealing as expected.

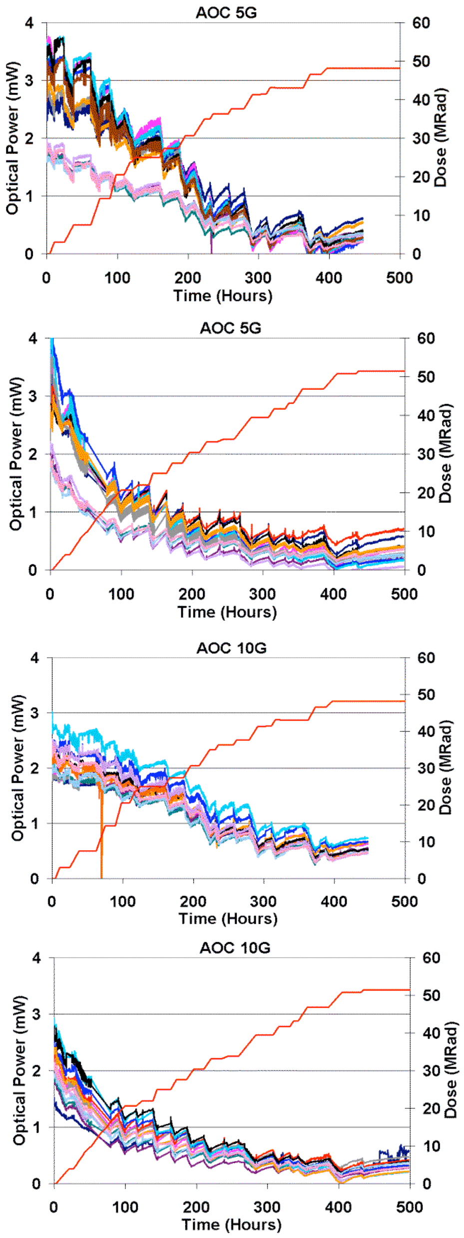

Figure 7: Optical power as a function of time (dosage) for the AOC VCSEL arrays that transmitted data to the control room. The power decreased during the irradiation but increased during the annealing as expected.

IV. NOVEL OPTICAL PACKAGE

We have developed a new novel package for the VCSEL and PIN arrays. The package is as compact the package provided by Academic Sinica, Taiwan for the current ATLAS pixel optical link. However, the base is fabricated using BeO instead of PCB for much better removal of the heat produced by the VCSEL which is the major heat source in the opto-link. The through hole vias for connecting to the anode and cathode pads on an array are replaced by three dimensional traces that go over the edge of the BeO base as shown in Fig. 8. Wire bonds connect the driver (receiver) chip to the VCSEL (PIN) array. This avoids the need for the challenging soldering of the micro-leads (250 μm width) to the BeO opto-board as it is difficult to supply sufficient heat to a tiny lead to attach to a trace on an excellent conductor. Moreover, the traces can be rewire bonded for diagnostics and rerouting purposes as sometimes needed, especially during the R&D phase of a project.

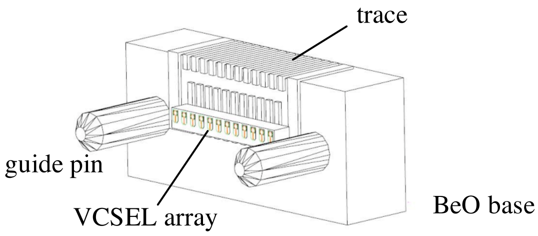

Figure 8: An optical package based on BeO.

The precise alignment of a VCSEL array to a MT ferrule is critical to achieve good optical power coupling; the alignment of a PIN array is much less critical because of the relatively large light sensitive area. Since the fibre ribbon is precisely placed with respect to the holes of the two guide pins in a MT ferrule, we align the VCSEL with respect to the guide pins. As a first step in the fabrication process, the guide pins are attached to the BeO base using epoxy with the precise relative location fixed by a MT ferrule. A VCSEL or PIN array is then aligned with respect to the guide pins under a microscope. The photos of an assembled opto-pack are shown Fig. 9. It is evidence that the package is quite a bit smaller than the MT ferrule. We achieve good coupled optical power for the VCSEL arrays from various vendors as shown in Fig. 10. We have fabricated 35 VCSEL and 6 PIN opto-packs. All except one VCSEL opto-pack have good coupled optical power. In summary, we have demonstrated the principle of a compact opto-pack fabricated with BeO for heat management.

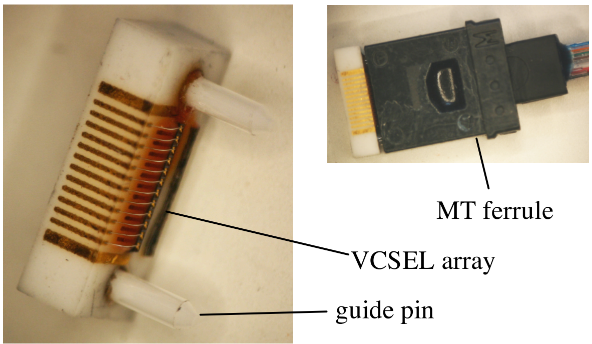

Figure 9: A fabricated opto-pack based on BeO.

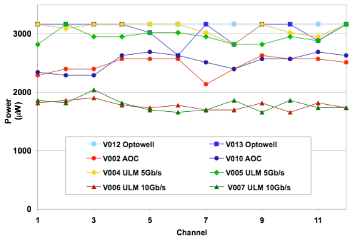

Figure 10: Coupled optical power of opto-packs fabricated with VCSEL arrays from various vendors.

V. SUMMARY

We have studied the bandwidth of the electrical and optical transmission lines of the current optical link of the ATLAS pixel detector. The results indicate that the micro twisted-pair cables can transmit signals up to 1 Gb/s. The bandwidth of the fusion spliced fiber ribbon has been measured to be greater than 2 Gb/s as reported in the previous conference [3]. The GaAs VCSEL arrays from three vendors have been found to have the radiation hardness suitable for the SLHC operation. The silicon PIN arrays by Truelight are also found to be radiation-hard as reported in the previous conference [3]. The current ATLAS pixel optical link architecture can therefore be used at the SLHC as a possible upgrade scenario. We have also demonstrated the feasibility of fabricating a novel opto-pack for housing VCSEL and PIN arrays with BeO as the substrate.

VI. ACKNOWLEDGEMENT

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VII. REFERENCES

[1] K.E. Arms et al., “ATLAS Pixel Opto-Electronics,” Nucl. Instr. Meth. A 554, 458 (2005).

[2] ATLAS Pixel Detector Technical Design Report, CERN/LHCC/98-13.

[3] K.K. Gan et al., “Bandwidths of Micro Twisted-Pair Cables and Fusion Spliced SIMM-GRIN Fiber and Radiation Hardness of PIN/VCSEL Arrays,” in Proceedings of the 12th Workshop on Electronics for LHC and Future Experiments, Valencia, Spain, 2006, edited by M. Letheren and S. Claude (CERN-2007-1), p. 223.

[4] See, for example, J.H.R. Schrader et al, IEEE-J. Solid-State Circuits 41, 990 (2006).

[5] MWS Wire Industries Twistite.

[6] I. Gregor, “Optical Links for the ATLAS Pixel Detector,” Ph.D. Thesis, University of Wuppertal (2001).

[7] A. Van Ginneken, “Nonionzing Energy Deposition in Silicon for Radiation Damage Studies,” FERMILAB-FN-0522, Oct. 1989.

[8] A. Chilingarov, J.S. Meyer, T. Sloan, “Radiation Damage due to NIEL in GaAs Particle Detectors,” Nucl. Instrum. Meth. A 395, 35 (1997).

[9] The fluences include a 50% safety margin.