

Bandwidths of Micro Twisted-Pair Cables and Fusion Spliced SIMM-GRIN Fiber and Radiation Hardness of PIN/VCSEL Arrays

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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 fibers spliced to rad-tolerant GRIN fibers. 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 and the fusion spliced fiber ribbon can transmit signals up to ~ 2 Gb/s. We have irradiated PIN and VCSEL arrays with 24 GeV protons and find at least one candidate PIN and one VCSEL array that can survive to the SLHC dosage.

I. INTRODUCTION

The SLHC is designed to increase the luminosity of the LHC by a factor of ten to $10^{35} \text{ cm}^{-2}\text{s}^{-1}$. 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 fiber ribbon fusion spliced to 70 m of rad-tolerant/medium bandwidth GRIN fiber ribbon. The optical signals are generated and sent using the PIN and VCSEL 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 a fusion spliced SIMM/GRIN fiber ribbon and the radiation hardness of PIN and VCSEL arrays.

II. BANDWIDTH OF MICRO TWISTED-PAIR CABLES

Commercial copper cables [3] 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 $100 \mu\text{m}$ (38 AWG) plus $25 \mu\text{m}$ of insulation, for an outer diameter of $150 \mu\text{m}$. The length of the twisted pairs varies from 81 to 142 cm. The wires for the endcap pixel detector are finer, $60 \mu\text{m}$ with $12 \mu\text{m}$ of insulation. The length of these copper twisted pairs is ~ 80 cm. The impedance of the twisted pairs is $\sim 75 \Omega$.

We have measured the bandwidths of micro twisted-pairs of various lengths, diameters, and numbers of turns per inch. The cables tested include [4]:

- 38 AWG ($100 \mu\text{m}$ core plus $25 \mu\text{m}$ of insulation): 5 TPI with 75Ω termination.
- 36 AWG ($127 \mu\text{m}$ core plus $9 \mu\text{m}$ of insulation): 5 TPI with 75Ω termination and 10 TPI with 100Ω termination.

For the bandwidth study, 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 current barrel cable has the fastest rise and fall times.

The eye diagrams produced by transmitting pseudo-random data of 650 Mb/s and 1 Gb/s in the current barrel 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 cable is adequate for transmitting signals at 640 Mb/s and that transmission at 1 Gb/s might be acceptable.

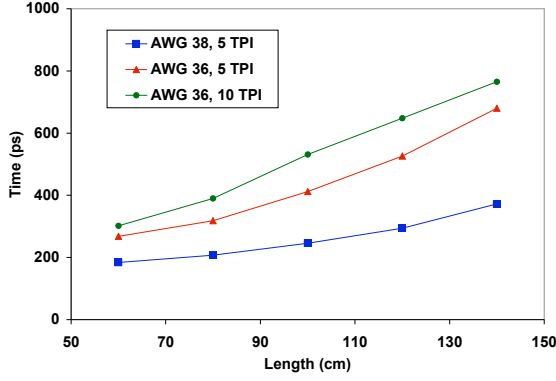


Figure 1: The rise times (20-80%) of the micro twisted-pairs vs. wire length for wires of various diameters and TPI.

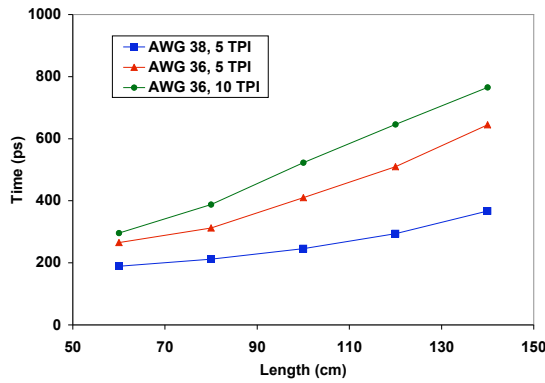


Figure 2: The fall times (20-80%) of the micro twisted-pairs vs. wire length for wires of various diameters and TPI.

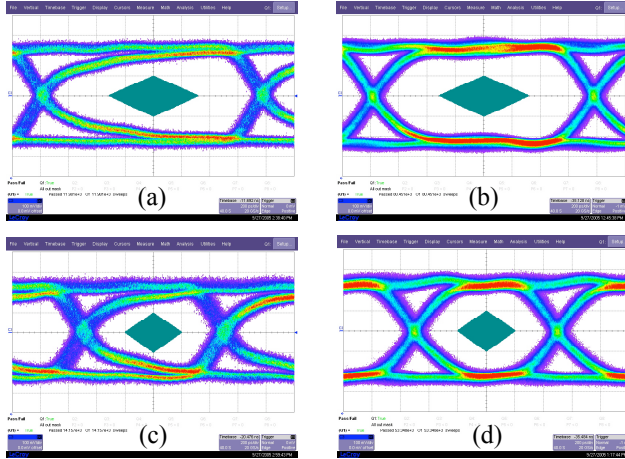


Figure 3: Eye diagrams for signals of (a) 650 Mb/s and (c) 1 Gb/s in a barrel cable of 1.4 m. (b,d) show the corresponding signals for a cable of 0.8 m.

III. BANDWIDTH OF FUSION SPLICED SIMM/GRIN FIBER

There are three kinds of commercial fibers available with each having different bandwidths. Single mode fiber has a core diameter of less than $10\ \mu\text{m}$, no modal dispersion, and hence the highest bandwidth. The other two fibers, GRIN and SIMM, are multi-mode fibers with core diameters of 50 or

$62.5\ \mu\text{m}$. The former has medium bandwidth and is radiation tolerant. The latter has lower bandwidth with a radiation-hard pure silica core. Each pixel optical link of the present pixel detector has 8 m of $50\ \mu\text{m}$ SIMM fiber ribbon fusion spliced to 70 m of $62.5\ \mu\text{m}$ GRIN fiber ribbon.

We have measured the bandwidth of 8 m of $50\ \mu\text{m}$ SIMM fiber fusion spliced to 80 m of $62.5\ \mu\text{m}$ GRIN fiber. The optical signal was generated with an 850 nm VCSEL, contained within a Finisar FTRJ-8519-1-2.5 fiber optic transceiver, and measured using the above oscilloscope with a 4.5 GHz optical to electrical converter. Resultant eye diagrams for pseudo-random signals of 650 Mb/s and 1 Gb/s are shown in Fig. 4. The mask shown is adapted from Fig. 38-2 of the Gigabit Ethernet Specification (IEEE Standard 802.3) and in accordance with the specification, a fourth-order Bessel-Thomson software filter is used to view the signals. We use a 1.5 Gb/s filter for the 2 Gb/s transmission as recommended. For the 1 Gb/s transmission, we choose the same bandwidth instead of the recommended 750 Mb/s to represent the waveform more accurately. It is evident from these results that the fiber can adequately transmit signals up to at least 1 Gb/s and hence the transmission bandwidth of the wire link will be the limiting factor in the present pixel detector transmission lines.

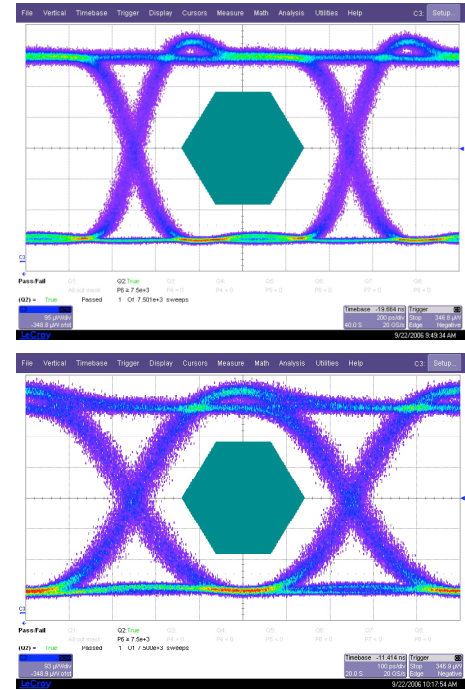


Figure 4: Eye diagrams for optical signals of (a) 1 and (b) 2 Gb/s in a fusion spliced SIMM/GRIN fiber.

IV. RADIATION HARDNESS OF PIN AND VCSEL ARRAYS

We use the Non Ionizing Energy Loss (NIEL) scaling hypothesis to estimate the SLHC fluences [5-7] 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, we expect the silicon component (PIN) to be exposed to a maximum total fluence of 2.5×10^{15} 1-MeV n_{eq}/cm^2 [8]. The corresponding fluence for a GaAs component (VCSEL) is 1.4×10^{16} 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 4.3 and 2.7×10^{15} p/cm², respectively. For simplicity, we present the results from the irradiations with dosage expressed in Mrad using the conversion factor, $1 \text{ Mrad} = 3.75 \times 10^{13}$ p/cm². The expected dosages are therefore 114 and 71 Mrad, respectively.

We irradiated four opto-boards with PIN and VCSEL arrays from various vendors using 24 GeV protons at CERN. Each board was instrumented with one silicon PIN array and a pair of GaAs VCSEL arrays. The PIN arrays were all fabricated by one vendor, Truelight, and the VCSEL arrays were fabricated by three vendors, Optowell, Advanced Optical Components (AOC), and ULM Photonics (two varieties, 5 and 10 Gb/s). On the opto-boards, each of 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 arrays before the irradiation. Figure 5 shows the LIV (Light-Current-Voltage) curves of the VCSEL arrays. 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.

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 as shown in Fig. 6. 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 (up to 20 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. Consequently both the A.O.C. and ULM 5 Gb/s arrays had no optical power at ~ 50 Mrad. The ULM 10 Gb/s arrays continued to have optical power of more than 100 μW up to 65 Mrad and the Optowell arrays survived up to at least 70 Mrad, the SLHC dosage. We believe that more arrays would have survived if we had more time for annealing.

The silicon PIN arrays survived the irradiation quite well. After the full SLHC dosage, the responsivities decreased to $\sim 35\%$ of the pre-irradiation level as shown in Fig. 7.

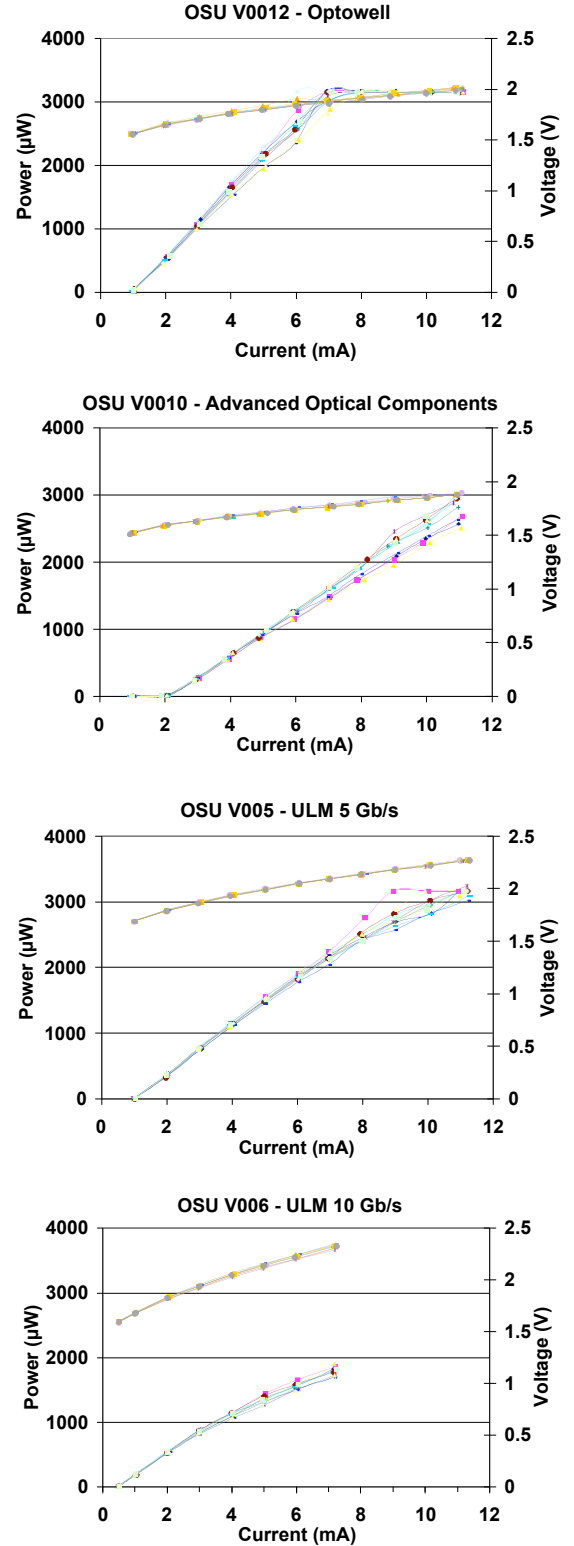


Figure 5: LIV curves of the four VCSEL arrays before irradiation.

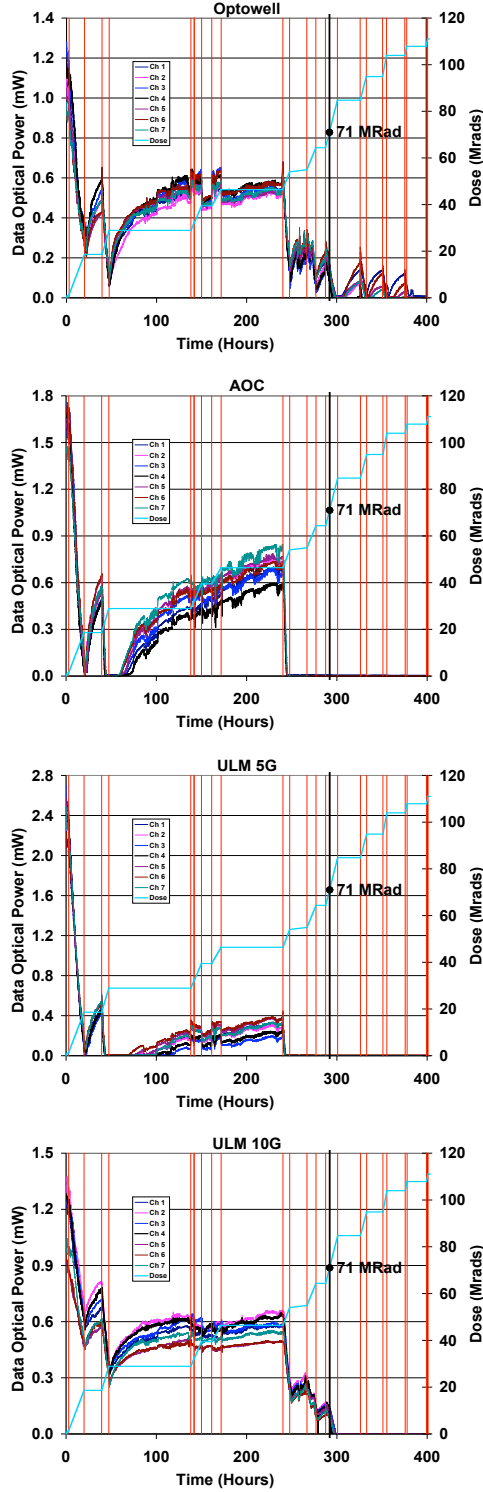


Figure 6: Optical power as a function of time (dosage) for the four VCSEL arrays that transmitted data to the control room. The power decreased during the irradiation but increased during the annealing as expected.

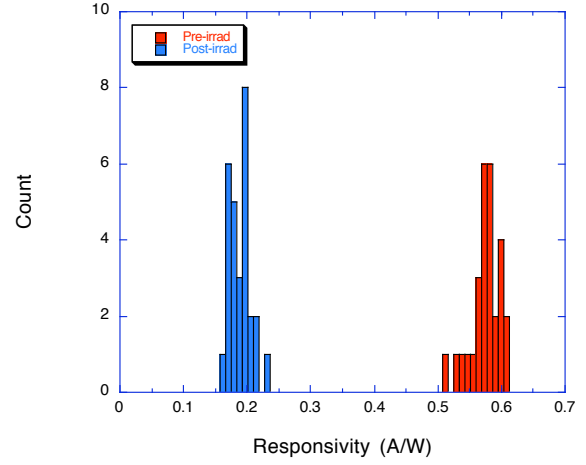


Figure 7: Responsivities of the four PIN arrays before (blue) and after (red) irradiation.

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 and the fusion spliced fiber ribbon can transmit signals up to 2 Gb/s. A silicon PIN and GaAs VCSEL array candidate have been identified to have radiation hardness suitable for the SLHC operation. The current infrastructure can therefore be used for the SLHC as a possible upgrade scenario.

VI. ACKNOWLEDGEMENT

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VII. REFERENCES

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