Radiation-Hard/High-Speed Data Transmission using Optical-Links

K.K. Gan[a,*], B. Abi[c], W. Fernando[a], H.P. Kagan[a], R.D. Kass[a], A. Law[a], M.R.M. Lebbai[b], F. Rizatdinova[c], P.L. Skubic[b], D.S. Smith[a]

[a]*Department of Physics, The Ohio State University, Columbus, OH 43210, USA*

[b]*Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019, USA*

[c]*Department of Physics, Oklahoma State University, Stillwater, OK 74078, USA*

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Abstract

The silicon trackers of the ATLAS experiment at the Large Hadron Collider (LHC) at CERN (Geneva) use optical links for data transmission. An upgrade of the trackers is planned for the Super LHC (SLHC), an upgrade of LHC with ten times higher luminosity. We investigate the radiation-hardness and bandwidth of various components for possible application in the data transmission upgrade. For the electrical connection between the front-end electronics and the optical link, we study the possible use of a micro twisted-pair cable. The bandwidth is measured to be 640 Mb/s for transmission up to 1.4 m and 320 Mb/s for transmission up to 4 m if the signal is pre-emphasized. For the optical devices, we irradiated VCSEL (Vertical-Cavity Surface-Emitting Laser) and GaAs PIN arrays from three vendors and silicon PIN arrays from one vendor. All arrays can be operated up to the SLHC dosage except the GaAs PIN arrays which have very low responsivities after irradiation. We have also demonstrated the feasibility of fabricating a novel optical package for housing VCSEL and PIN arrays with BeO (Beryllium Oxide) as the substrate for efficient removal of heat.

Keywords: SLHC; optical-link; bandwidth; micro twisted-pair cable; VCSEL; PIN

1. Introduction

Optical links are now widely used in high energy physics experiments for data transmission. The links substantially reduce the volume of metallic signal cables freeing up valuable detector space. In addition, the fibers eliminate the cross talk between metallic cables and electrical ground loops between the front-end electronics and the data acquisition system. The high bandwidth of opto-electronics is well suited for multiplexing many input channels and allows for introduction of error checking and error recovery transmission protocols. These features are especially important in experiments where radiation can induce Single Event Effects (SEE) in the digital electronics.

[*] Corresponding author. Tel.: +1-614-292-4124; fax: +1-614-292-8261; e-mail: gan@mps.ohio-state.edu.

The silicon trackers of the ATLAS experiment at the LHC use VCSELs to generate the optical signals at 850 nm and PIN diodes to convert the signals back into electrical signals for further processing. The devices have been proven to be radiation-hard for operation at the LHC.

The LHC will start operation in 2009. However, an upgrade of the collider, Super LHC, is already being planned for 2016. The SLHC is designed to increase the luminosity of the LHC by a factor of ten to 10^{35} $cm^{-2}s^{-1}$. Accordingly, both the required data bandwidth and radiation-hardness of the detector are expected to increase by a similar factor. As an indication of the scale of the project, the current pixel detector of the ATLAS experiment has 1,744 modules and data from most of the modules are transmitted at 80 Mb/s. For SLHC, the much higher occupancy dictates a reduction in the pixel size to limit the increase in the data rate for each pixel module. The higher occupancy also implies that the pixel detector will expand to larger radius, replacing the silicon strip detector. Consequently the number of pixel modules will increase by a factor of 2-3. The date rate from each module is expected to be between 160 and 320 Mb/s. The data from multiple modules will be multiplexed to a higher data rate, > 3 Gb/s, to limit the number of optical links needed to a manageable level. In this paper, we present a study of various components for possible application at SLHC. This includes the bandwidth of a micro twisted cable for the transmission between a pixel module and a multiplexer, the radiation-hardness of the VCSEL and PIN arrays, and a novel opto-pack for housing VCSEL and PIN arrays with BeO as the substrate for efficient removal of the heat.

2. Bandwidth of Micro Twisted-Pair Cables

Commercial copper cables [1] can transmit several Gb/s over tens of meters. However, the diameters of these cables are too large for the ATLAS 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 optical module (opto-board). For barrel pixel detectors, each wire is aluminum 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 previously measured the bandwidths of micro twisted-pairs of various lengths, diameters, and numbers of turns per cm [2]. We transmitted LVDS pseudo-random data (2^{23} bits) 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 study revealed that the current barrel cable is close to optimum given the space constraint. Figure 1(a) shows the eye diagrams produced by transmitting pseudo-random data of 640 Mb/s in the cable. The masks shown are adapted from Figure 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. It is evident that the cable is adequate for transmitting signals up to 640 Mb/s. For SLHC, we are interested in transmitting the signal at 320 Mb/s up to 4 m before multiplexing to ease the space constraint and radiation-hardness requirement. We have therefore extended the study to longer cable and find that the transmission is adequate only up to 3 m as shown in Fig. 1(b). To reach the target length of 4 m, the high-frequency components of the signal must be pre-emphasized in the signal driver to compensate for transmission loss in long cable. We use the pre-emphasis circuitry within the Stratix GX board with an interface that acts like a two-tap Finite Response filter (FIR). Figure 1(c) shows that the received signal is quite acceptable after the pre-emphasis.

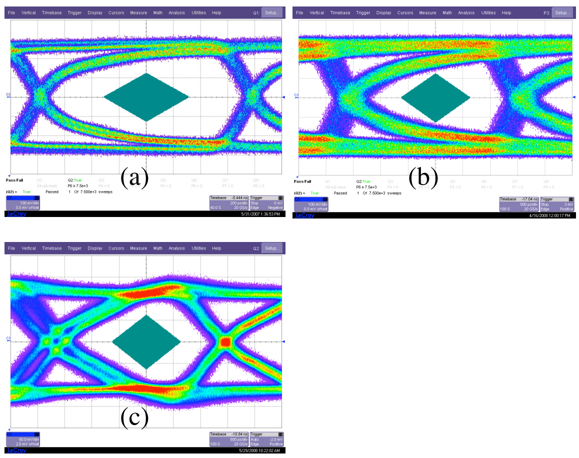

Figure 1: Eye diagrams of (a) 640 Mb/s signal after 1.4 m of cable, (b) 320 Mb/s signal after 3 m of cable, (c) pre-emphasized 320 Mb/s signal after 4 m of cable.

3. Radiation-Hardness of VCSEL and PIN Arrays

We use the Non Ionizing Energy Loss (NIEL) scaling hypothesis to estimate the SLHC fluences [3-5] at the present optical link location (PP0) of the ATLAS pixel detector. 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 [6]. 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 with each board instrumented with one silicon PIN and two GaAs VCSEL arrays from various vendors using 24 GeV protons at the T7 facility of CERN. The PIN and VCSEL arrays coupled to radiation-hard ASICs produced for the current pixel optical link [7], the DORIC (Digital Opto Receiver Integrated Circuit) and VDC (VCSEL Driver Chip). Furthermore, the opto-boards were mounted on a shuttle system that enabled us to easily move in and out of the beam for annealing of the VCSEL arrays. The test system monitored various parameters of the opto-boards throughout the irradiation. In 2007, we also irradiated GaAs PIN arrays from three vendors. These devices were biased during the irradiation but not monitored due to space constraint. The devices irradiated are summarized in Table I.

Vendor	VCSEL	BW	PIN	BW
Optowell	2	2.5	2	2.5
AOC	4	5	2	5
AOC	4	10		
ULM	2	5	2	4.25
ULM	4	10		

Table I. Summary of the number VCSEL and PIN arrays of various vendors used in the irradiation together with the bandwidth (BW) in Gb/s.

The test system monitored the optical power of the VCSEL arrays vs. dosage. In the 2006 irradiation, we found that all arrays continued to produce good optical power up to the SLHC dosage but the degradation with dosage was quite drastic [8]. We believe that the 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. Figure 2 shows the optical power vs. dosage for the various arrays (The arrays from the opto-boards with the worst optical power are shown.) 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. Unfortunately, there was insufficient time for a complete annealing. However, all devices continued to produce good optical power up to the SLHC dosage of 34 Mrad, except ULM arrays that were least radiation-hard, consistent with the observation of 2006.

The arrays were returned to The Ohio State University after ~140 days for an extended annealing. It is evident from Fig. 2 that the annealing was slow and some of the ULM channels never recovered and hence are not as radiation-hard.

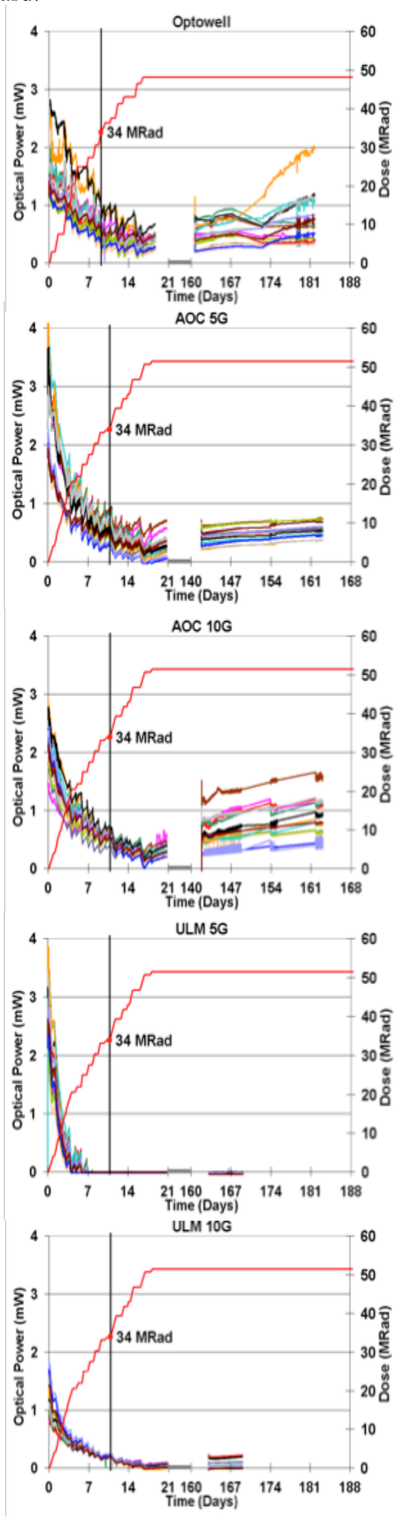

Figure 2: Optical power as a function of time (dosage) for various VCSEL arrays that transmitted data to the control room. The power decreased during the irradiation but increased during the annealing as expected. The arrays were returned to The Ohio State University after ~140 days for an extended annealing and there are some recovery of the power except the ULM 5 Gb/s arrays.

We irradiated silicon PIN arrays from Taiwan in 2006 and found that the responsivities decreased by 65% after the radiation, which is acceptable for the SLHC application. In 2007, we irradiated GaAs VCSEL arrays by AOC, Optowell, and ULM and found that the responsivities decreased by ~ 90% which is not acceptable for the SLHC application. We plan to repeat the irradiation this year together with devices from other vendors.

4. Novel Optical Package

We have developed a novel package for the VCSEL and PIN arrays as shown in Figs. 3 and 4. The package is as compact as the package provided by Academic Sinica, Taiwan for the current ATLAS pixel optical link [7]. However, the base is fabricated using BeO instead of PCB for much better removal of the heat produced by the VCSEL, 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. 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.

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. We achieve good coupled optical power for the VCSEL arrays from various vendors. This demonstrates the principle of a compact opto-pack fabricated with BeO for heat management.

5. Conclusions

We have studied various components for use in the optical data transmission for SLHC. The results indicate that the micro twisted-pair cable currently used in the barrel region of the ATLAS pixel detector can transmit signals up to 640 Mb/s for up to 1.4 m. The transmission distance can be extended up to 4 m for a pre-emphasized 320 Mb/s signal. The VCSEL arrays of two vendors, Optowell and AOC (5 and 10 Gb/s), are found to be acceptable for the SLHC application. GaAs PIN arrays from three vendors were tested. The responsivities decrease by a factor of ten and hence the arrays are not acceptable. We have also demonstrated the feasibility of fabricating a novel opto-pack for housing VCSEL and PIN arrays with BeO as the substrate for efficient removal of the heat.

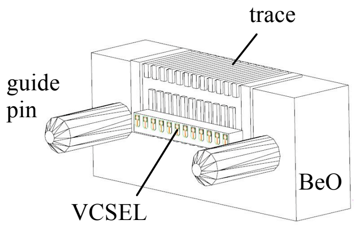

Figure 3: An optical package based on BeO.

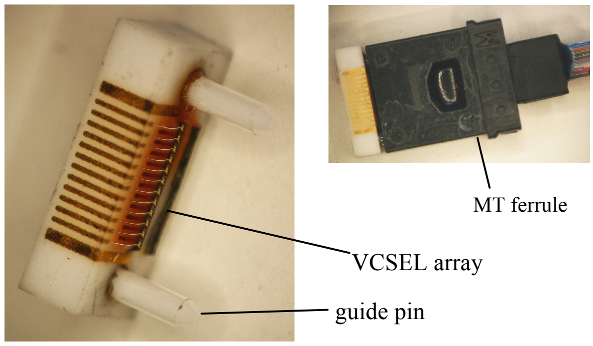

Figure 4: A fabricated opto-pack based on BeO.

Acknowledgement

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Reference:

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