NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Optical Data Transmission for Semiconductor Trackers

K.K. Gan[a*]

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

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Abstract

This is a review of technologies that might be used for optical data transmission for semiconductor trackers at the High-Luminosity Large Hadron Collider (HL-LHC) at CERN, Geneva, Switzerland. The technology being proposed uses a compact VCSEL (Vertical Cavity Surface Emitting Laser) array to transmit data in a multi-fiber ribbon. The R&D results from three groups are presented. This includes the high-speed optical modules with the signal equalization being developed by the Ohio State/Siegen group, the transmitter/receiver optical modules being developed by the Versatile Link group at CERN, and two optical packages for housing VCSEL arrays being tested by the Academia Sinica group.

Keywords: optical link; HL-LHC upgrade; VCSEL array; radiation hardness

1. Introduction

The use of VCSEL arrays allows the fabrication of a compact optical module for high-speed data transmission. The compact design is enabled by readily available commercial high-speed VCSEL arrays. Modern VCSELs are humidity tolerant and hence no hermitic packaging is needed. With the use of a 12-channel array operating at 10 Gb/s per channel, an array based optical module can deliver an aggregate bandwidth of 120 Gb/s. With a standard spacing of 250 μm between two adjacent VCSELs, the width of a 12-channel array is only slightly over 3 mm. This allows the fabrication of a rather compact optical module for the installation in locations where space is at a premium. The use of a fiber ribbon also reduces the fiber handling. Moreover, a fiber ribbon is less fragile than a single-channel fiber. These advantages greatly simplify the production, testing, and installation of optical links.

VCSEL arrays are widely used in off-detector data transmission in high-energy physics [1]. The first implementation [2] of VCSEL arrays for on-detector application is in the optical links of the ATLAS pixel detector. The experience from the operation of this first generation of array-based links was satisfactory. The ATLAS experiment therefore continued to use VCSEL arrays in the second-generation optical links [3] for a new layer of the pixel detector, the insertable barrel layer (IBL), installed in early 2014 during the

* Corresponding author. Tel.: +001-614-292-4124; e-mail: gan@mps.ohio-state.edu.

long shutdown (LS1) to prepare the Large Hadron Collider (LHC) for collisions at the center-of-mass energy of 13 TeV. In addition, ATLAS also decided to move the optical links of the original pixel detector to a more accessible location. The replacement optical links are also array based.

The optical links for the semiconductor trackers for HL-LHC will be array based in order to satisfy the severe space constraint. In this proceeding, the results from three R&D projects will be presented.

2. Opto-Board

The optical links of the installed ATLAS pixel detector are based on the opto-board concept. In fact, this is the second deployment of the opto-board concept for the pixel detector as noted above. The Ohio State/Siegen group[1] is therefore pursuing the R&D to study the feasibility of implementing the opto-board concept for the ATLAS pixel detector of HL-LHC.

The opto-board is a miniature printed circuit board (PCB) as shown Figure 1. A VCSEL array driver ASIC is mounted on the opto-board next to an opto-pack that houses a VCSEL array. This keeps the length of the wire bonds between the ASIC and the VCSEL array to a minimum to diminish the parasitic capacitance and inductance of the wire bonds, which allows the ASIC to drive the VCSELs at high speed. The PCB has a thick copper back plane (1.0 mm) for the thermal management. A MTP[2] barrel attached to an aluminum brace is secured to the opto-board via a screw. A fiber ribbon terminated with a MTP connector can be inserted into the MTP barrel to receive the optical signal from the VCSEL array. An electrical connector[3] is attached to the PCB to transmit the high-speed data from a pixel module to the VCSEL array driver ASIC. The high-speed electrical signals from the connector to the ASIC are transmitted using differential pair transmission lines with controlled impedance on the PCB.

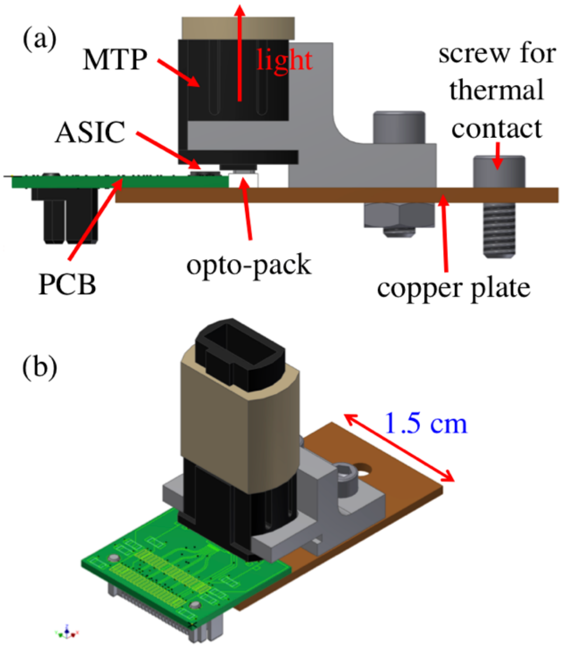

Fig. 1. (a) Schematic drawing of an opto-board together with a MTP barrel fastened to the opto-board for the insertion of a fiber ribbon terminated with MTP connector to receive the optical signal from the VCSEL array. (b) A three-dimensional rendition of the setup.

The VCSEL array driver ASIC [4] was developed under the US Collider Detector R&D (CDRD) program of DOE. We prototyped the ASIC using the 65 nm CMOS process of TSMC[4]. Each ASIC contains four channels. In this design, only the core transistors of the technology are used. The core transistors offer the thinnest oxide available and thus the design benefits from the known improvement in total ionizing dose radiation tolerance provided by thinner oxides [5]. Each VDC channel includes two 8-bit DACs, one for setting the modulation current and the other for setting the bias current. The DAC

[1] Ohio State/Siegen group: K.K. Gan, B. Tar/P. Buchholz, S. Heidbrink, W. Stroh, M. Ziolkowski.

[2] MTP connector, US Conec Ltd.

[3] LSHM connector, Samtec Inc.

[4] Taiwan Semiconductor Manufacturing Company, Limited.

settings are stored in single event upset (SEU) tolerant registers.

All four channels in the prototype ASIC are operational with bit error rate of less than 1.3 x 10^{-15} with all channels active using pseudo random bit strings (PRBS) as the input. We irradiated eight opto-boards with prototype ASICs using 24 GeV/c protons at the CERN PS irradiation facility. In four opto-boards, each ASIC drove a resistive load while in the other four opto-boards, each ASIC drove a VCSEL array[5]. The former allowed the evaluation of the ASICs should the VCSEL arrays were not as radiation hard as expected. The opto-boards with VCSEL arrays attached were exposed to a dose of 4.58 x 10^{14} protons/cm^2, corresponding to an ionizing dose of 12.2 Mrads and a non-ionizing dose of 2.69 x 10^{14} 1-MeV n_{eq}/cm^2, assuming that the radiation damage in the VCSEL scales with the non-ionizing energy loss (NIEL) in the GaAs [6-7]. The opto-boards containing no VCSELs were exposed to a dose of 2.78 x 10^{15} protons/cm^2, corresponding to an ionizing dose of 74.0 Mrads.

All ASICs were powered and monitored during the irradiation but at reduced speeds because it was not practical to install high-speed electrical cables at the irradiation facility in addition to the fiber bundles. The opto-boards with VCSEL arrays were periodically removed from the proton beam to allow the annealing of the VCSELs that occurred naturally when powered. All channels were operational at the end of the irradiation. The optical eye diagram of one channel after irradiation is compared to that before irradiation in Fig. 2 for 5 Gb/s operation, the expected data transmission speed (see below) of the ATLAS pixel detector at HL-LHC. The optical amplitude decreases from ~2.1 to ~1.2 mW. The opening of optical eye diagram is smaller but the device still operates error free for more than 30 minutes, corresponding to a bit error rate of BER < 5x10^{-14}, with all channels active.

The ATLAS pixel detector at the HL-LHC plans to transmit data from the pixel modules at 5 Gb/s via 5.5 m of skinny cables[6] to optical modules. The signal will be badly distorted due to the attenuation of high frequency components. An equalization circuit is needed to restore the high frequency response. Figure 3 shows the circuit design with 4-tap Continuous Linear Time Equalization (CTLE) for equalization of the frequency response across the frequency of interest. The improvement of the signal at each tap is shown in Fig. 4. The eye is closed at end of the cable but it is progressively being open at each tap and it is quite open at the fourth tap. The result is preliminary and the circuit is being improved.

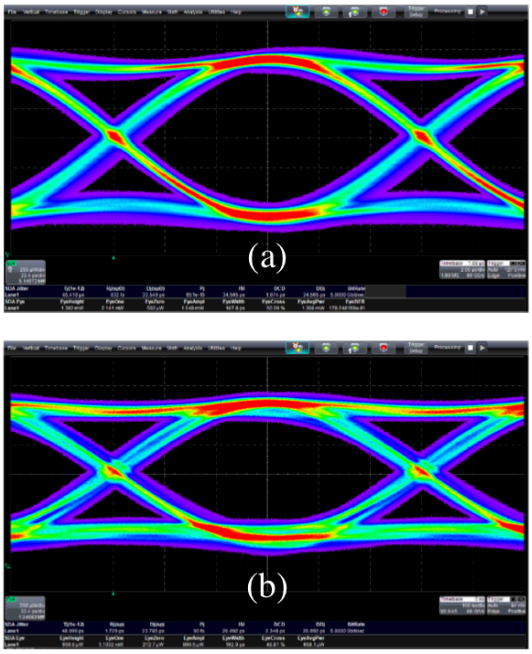

Fig. 2. Optical eye diagram of a VCSEL operating at 5 Gb/s before (a) and after (b) irradiation.

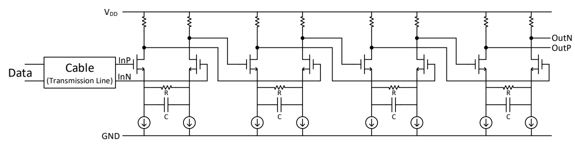

Fig. 3. 4-tap Continuous Linear Time Equalization (CTLE) circuit to equalize the frequency spectrum of a signal after emerging from a 5.5 m of skinny cable.

[5] The VCSEL array used is V850-2174-002, fabricated by Finisar Corporation.
[6] M. Kocian, ACES workshop, 2016.

3. Optical Modules from Versatile Link Project

Versatile Link Plus project[7] is a consortium of institutions formed to develop optical transmitter and receiver for the HL-LHC detector upgrades. An optical module, VTRx, can contain one PIN diode and one VCSEL or a four-channel VCSEL array as shown in Fig. 5. Optical signal (clock and command) at 2.5 Gb/s from off-detector induces an electrical signal on the PIN diode and the signal is processed by the Trans-Impedance Amplifier (TIA) before being sent to the low power gigabit transceiver (lpGBT)[8] ASIC for decoding. Data at 5 or 10 Gb/s from the front-end electronics are serialized by the lpGBT and sent to laser driver ASIC (LDD) to transmit optically to the counting room.

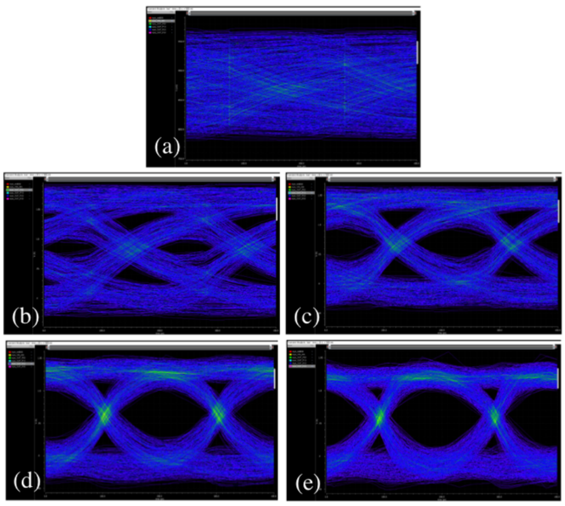

Fig. 4. Eye diagram of the electrical signal at the end of 5.5 m of skinny cable (a) and output at each of the four taps (b-e).

The optical modules have been extensively prototyped and tested. Figure 6 shows the optical eye diagram for a 4-channel VCSEL array. The VCSEL array delivers good optical power, ~2 mW, and the eye is quite open at 10 Gb/s. Figure 7 shows that the receiver can operate error free down up low optical power as indicated by the bit error rate as a function of the optical modulation amplitude (OMA) with no interference with the transmitter. The optical modules have been verified to be radiation hard up to 1 MGy or $3x10^{15}$ n/cm^2.

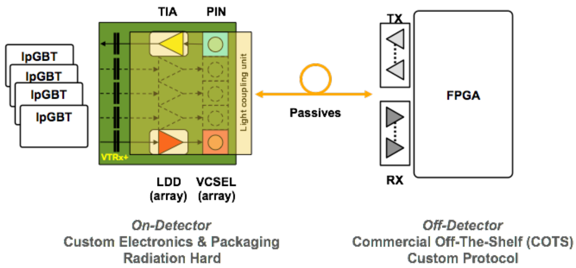

Fig. 5. Schematic of the data transmission system of the Versatile Link project.

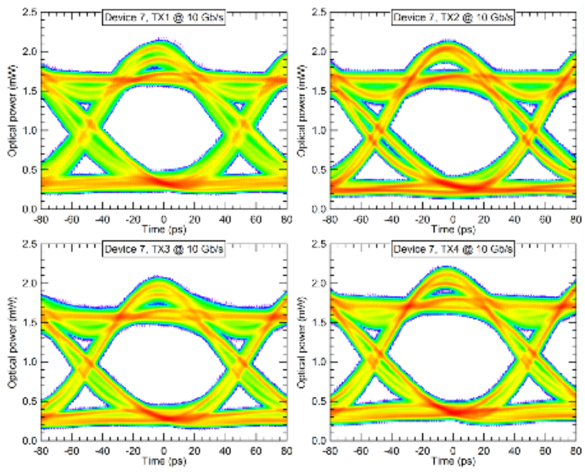

Fig. 6. Optical eye diagram for a 4-channel VCSEL array in a VTRx.

The project is currently in the final phase of prototyping. Figure 8 shows a prototype VTRx with an optical package attached. One not so nice feature of the VTRx is that the fiber ribbon (pigtail) is permanently attached, complicating the installation procedure. The other not so nice feature is the mixing of the optical receiver and transmitter signals in a fiber ribbon. This requires a complicated and costly rerouting of the optical signals into fiber ribbons that contain receiver and transmitter signals only in order to be in compliant with the industrial standard for off-detector optical electronics. However, the project

[7] https://espace.cern.ch/project-Versatile-Link-Plus/SitePages/Home.aspx
[8] https://espace.cern.ch/GBT-Project/default.aspx

does benefit from the large volume production because VTRx will be used widely by multiple sub-detectors, resulting in reduced production cost.

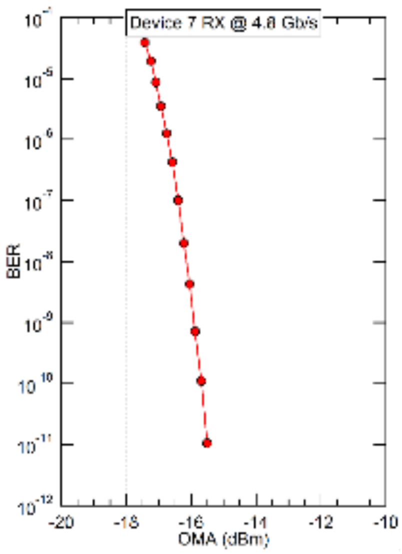

Fig. 7. Bit error rate of a receiver in a VTRx as a function of the optical modulation amplitude (OMA).

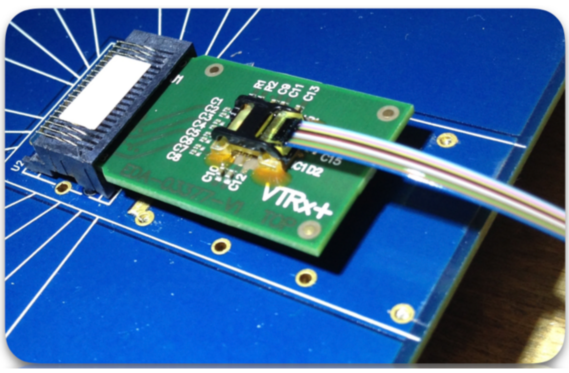

Fig. 8. A VTRx with an optical package attached to a fiber ribbon.

4. Compact Optical Packages

Two compact optical packages have been evaluated[9] by Academia Sinica, Taipei. Figure 9 shows the package manufactured by FOCI while Fig. 10 shows the schematic drawing for the package by Murata. The use of these optical packages would take advantage of the volume industrial production. The challenge is to convince the vendors to produce optical packages for the trackers because of the relatively small volume.

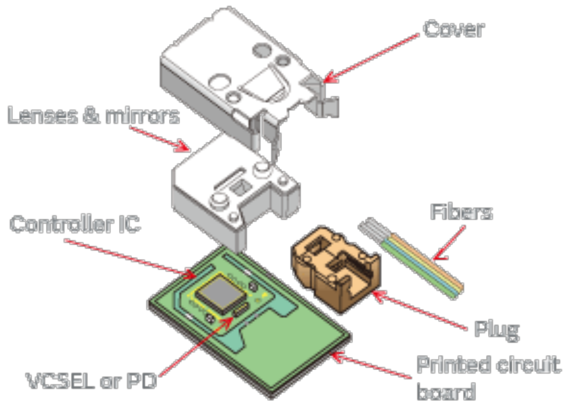

Fig. 9. A compact optical package by FOCI.

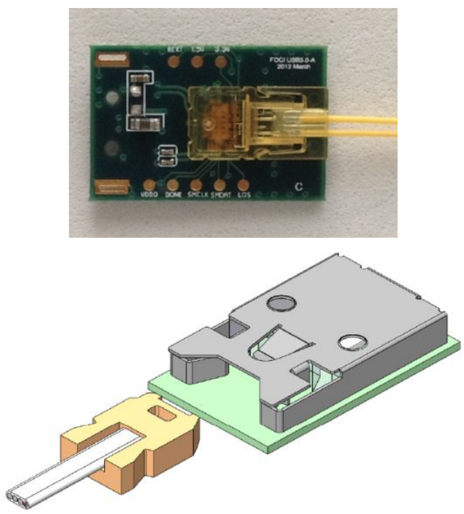

Fig. 10. A compact optical package by Murata.

[9] Suen Hou, private communication.

5. Summary

Three R&D projects are presented in this Proceedings that use optical arrays as the compact/low-mass solution for the data transmission of a tracker. Optical arrays are now widely accepted as the solution for data transmission.

Acknowledgments

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