Design, Production, and Reliability of the New ATLAS Pixel Opto-Boards

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ABSTRACT: New fiber optical transceivers, opto-boards, were designed and produced to replace the first generation opto-boards installed in the ATLAS pixel detector and for the new pixel layer, the insertable barrel layer (IBL). Each opto-board contains one 12-channel PIN array and two 12-channel VCSEL arrays along with associated receiver and driver ASICs. The new opto-board design benefits from the production and operational experience of the first generation opto-boards and contains several improvements. The new opto-boards have been successfully installed. Additionally, a set of the new opto-boards have been subjected to an accelerated lifetime experiment at 85 C and 85% relative humidity for over 1,000 hours. No failures were observed. We are cautiously optimistic that the new opto-boards will survive until the shutdown for the detector upgrade for the high-luminosity Large Hadron Collider (HL-LHC).

KEYWORDS: optical transceiver; LHC.

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1. Introduction

The Large Hadron Collider (LHC) at CERN (Geneva) is now the highest energy and luminosity collider in the world. The LHC is currently in a period of maintenance in order to increase the center-of-mass energy from 7 to 13 TeV. The pixel detector of the ATLAS experiment contains four barrel layers and three disks on each end. The inner barrel layer (insertable barrel layer, IBL) is a new additional layer installed during this shutdown. New opto-boards have been fabricated for the pixel system for two reasons: 1) the IBL requires a new version of opto-board; 2) the opto-boards will be installed in a more accessible location in case servicing is needed in the next ten years.

VCSEL (Vertical Cavity Surface Emitting Laser) and PIN arrays mounted in commercial modules have been widely deployed in off-detector data communication in high energy physics since there are no space or radiation constraints. The pixel detector of the ATLAS experiment is the first to deploy arrays for on-detector data communication. The experience has been quite positive. An analysis of the extracted opto-boards revealed a failure rate of 0.1% for the boards fabricated by The Ohio State University. Consequently, the new opto-boards are also array based. The use of arrays greatly simplifies the production, testing, and installation. In this paper, we will present the design, production, and a reliability study of the new opto-boards.

2. Design of the New Opto-Boards

Each new opto-board contains two VCSEL arrays and one PIN array to transmit and receive optical signals. A picture of a new opto-board is shown in Fig. 1. Each optical array is mounted on an optical package (opto-pack) [1]. Each array is wire bonded to two four-channel ASICs [2]. A picture of opto-packs is shown in Fig. 2. The new opto-board consists of a PCB bonded to a 2 mm thick copper plate for thermal management. The copper plate replaces the BeO substrate from the first generation opto-board, resulting in significant cost savings.

The design of the new opto-board is similar to the first generation opto-boards [2] but includes several improvements based on the production and operational experience of the first generation opto-boards. The improvements include:

- Replacement of a custom optical connector with a commercial MPO connector for easier mating and de-mating.
- Use of an opto-pack with the optical array mounted on a BeO substrate instead of a PCB for efficient heat removal.
- Use of wire bonds to connect the opto-packs to the opto-boards. This replaces soldering in the first generation opto-boards which were built on BeO substrates. Soldering to a micro-lead in an opto-pack to a trace on a BeO opto-board was a major challenge as supplying too much heat would cause the lead to detach inside the opto-pack while supplying too little heat would produce a cold solder. In fact, this was the major contributor to the optical link failures in the previously installed opto-boards.

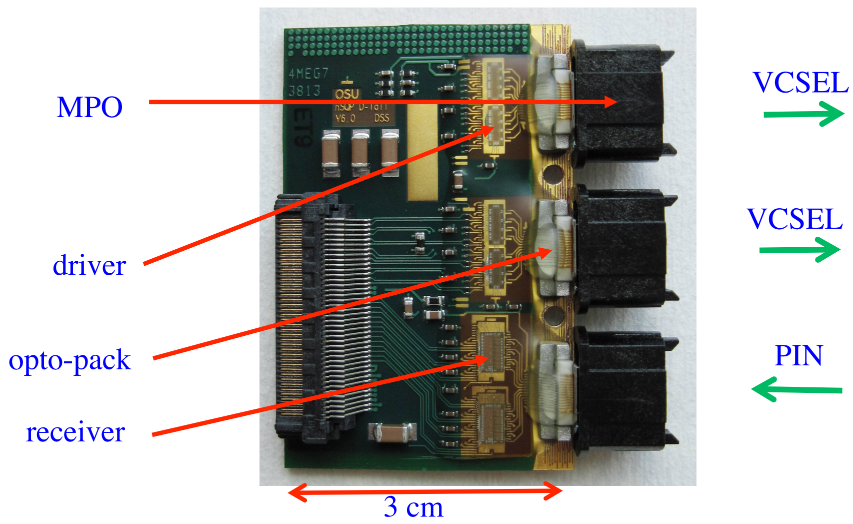

Figure 1: Picture of an opto-board.

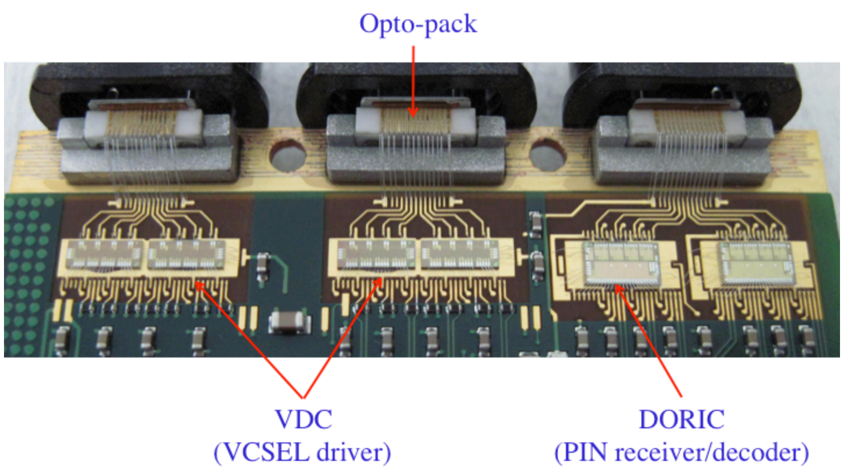

Figure 2: Picture of three opto-packs connected to three pairs of ASICs via wire bonds.

There are three opto-board flavors. Two of these ("D" and "B" type opto-boards) are for the three outer barrel layers and disks. These boards contain seven links to transmit Trigger-Timing-Control (TTC) information to the detector and fourteen data links for sending data to the counting room. The third flavor is for the IBL with eight TTC links and sixteen data links. Both the PIN [3] and VCSEL [4] arrays are 12-channel devices and hence some channels are not used. The pixel detector needs a total of 300 opto-boards. We produced about 400 opto-boards, including boards for test systems and spares. This corresponds to about 8,500 optical links in total.

3. Production Problems of the New Opto-Boards

The production procedure was defined after the pre-production of small numbers of opto-boards. Despite this exercise, we still encountered two problems that required an update to the fabrication procedure.

The first problem was caused by inadequate adhesion strength holding the opto-packs to the opto-boards. Several opto-packs detached at various stages of the production. This was due to the small epoxy contact area between the opto-pack and the opto-board. This problem was fixed using the following procedure: i) an aluminum brace is glued to both the opto-pack and the opto-board to greatly increase the effective epoxy contact area, ii) the surface of the aluminum brace is sandblasted and the contact area on the opto-board scored to increase the adhesion. An opto-pack with an aluminum brace is shown in Fig. 3. With these changes, an opto-pack cannot be removed from an opto-board without the use of excessive force.

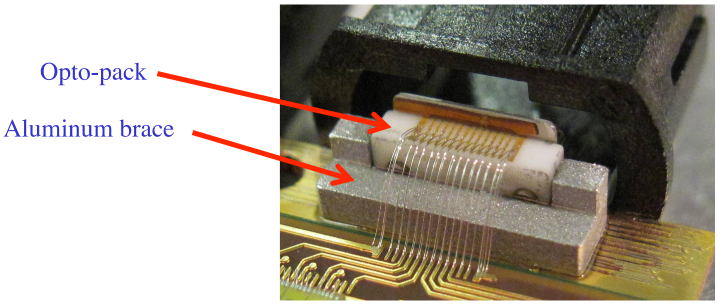

Figure 3: Picture of an opto-pack which consists of a BeO substrate with traces for wire bonds on one side and an VCSEL array mounted on the other side facing the MPO connector. Also shown is the aluminum brace.

The second problem was caused by a bad batch of epoxy used to attach MPO connectors to opto-boards. Early in the production, several MPO connectors (< 10) were detached. Investigation of the problem revealed that the color of the epoxy used was different from that of the later batch. We decided to remount the connectors on all 22 opto-boards that were constructed using this older batch of epoxy. We took advantage of this repair to test the reliability of the adhesion of the MPO connectors to the opto-boards. Thirty insertion tests (mating/de-mating) were performed on 40 of the 66 MPO connectors before the MPO connectors were replaced and none detached. This indicates the connection is reliable under normal operation even with the epoxy of questionable quality. Nineteen boards were successfully recovered.

4. Quality Assurance of the New Opto-Boards

Each new opto-board must pass a quality assurance (QA) procedure to ensure reliable operation for the next ten years. The opto-board was powered during the QA procedure. The QA procedure is similar to that used for the first generation opto-boards. The procedure is:

- Burn-in at 50 C for 72 hours
- 10 thermal cycles from 0 to 50 C with 2 hours per cycle, including an hour soak at 50 C

- Pass the electrical and optical QA requirements,

The production was smooth and a total of 393 good opto-boards were produced over a period of nine months. A total of 28 boards failed to pass the QA for various reasons as summarized in Fig. 4. The failures were analyzed for a possible indication of a production procedure fault or long term reliability problem. The following is an analysis of the failures other than those due to trivial mistakes in the production:

- Two PIN receiver chips (DORICs) had bad duty cycle. This is probably due to the lack of precision in the measurement of the duty cycle using a probe card with long leads, resulting in the two ASICs with bad duty cycle being accepted for mounting on the opto-boards.
- One VCSEL driver chip (VDC) could not control the drive current on the connected VCSEL array. This premature failure of a VDC is not understood and is a concern. However, we did not observe any similar failure mode in the post-mortem of the first generation opto-boards which used the same ASICs. Given this, the failure appears to be infant mortality of the ASIC in question and was successfully uncovered by the burn-in/thermal cycling/QA procedure.
- Eight VCSEL arrays ("Low IVDD") had low optical power. Investigation revealed that five of the arrays were not properly glued to the BeO substrates in the opto-packs. The other three failures were probably due to the fact that the opto-boards were thermal cycled down to -25 C as was used in the QA of the first generation opto-boards. However, this is outside the operational range of 0-50 C recommended in the specification sheet of the VCSEL. After this mistake was discovered, we thermal cycled all subsequent opto-boards between 0 and 50 C and no further problems were found.
- Four PIN arrays had large leakage currents. This problem will be discussed next.

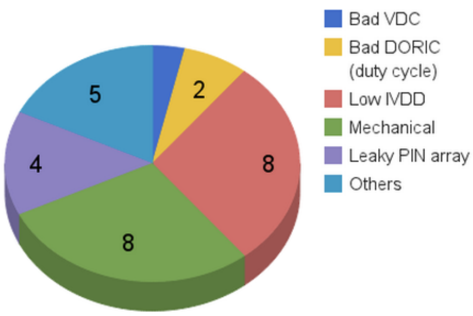

Figure 4: Summary of the various types of failures in the produced opto-boards.

5. Accelerated Lifetime Test

The new opto-boards must be fully functional for the next ten years. It is therefore critical that a sample of opto-boards survive an accelerated lifetime test for at least one thousand hours in a chamber operated at 85 C and 85% relative humidity. This is one of reliability tests used in the optical electronics industry. Each VCSEL channel was operated at 10 mA of current (pk-pk) during the test. We performed weekly measurements of the optical powers of the VCSEL arrays, dark current in the PIN array, and current consumption of each opto-board. In addition, a test of operation with no bit errors in all channels was performed.

Two opto-boards were used in the initial test, for a total of 16 PIN channels and 32 VCSEL channels. The test was terminated at 1,000 hours. All VCSEL channels remained operational but the PIN arrays had a drastic increase in the dark current as shown in Fig. 5. The PIN arrays were biased at 10 V, the maximum operating voltage in the specification sheet. We communicated with the manufacturer of the PIN arrays regarding the impact of the PIN bias voltage on the lifetime. The manufacturer recommended that we operate the arrays at 5 V. This is because the bias voltage and operating temperature are the dominant acceleration factors in the aging of the PIN arrays.

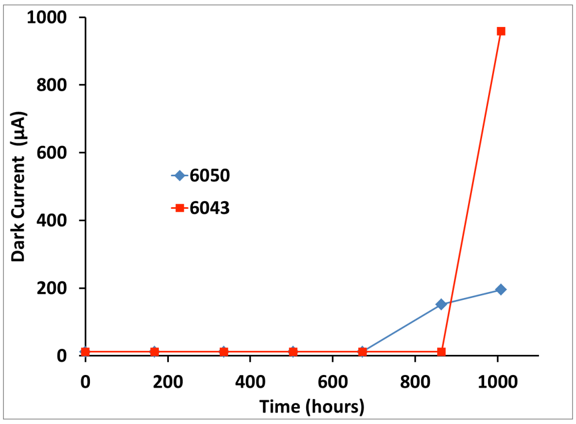

Figure 5: Leakage current in two PIN arrays as a function of time in a chamber operated at 85 C and 85% relative humidity.

We then started a new accelerated lifetime test with four opto-boards at the reduced PIN bias voltage. At the time of this conference, two boards have accumulated 1,560 hours of operation while the other two have accumulated 1,740 hours. All boards are fully operational with no increase in the dark current in the PIN arrays. This is reassuring given that the PIN arrays were operated with 10 V bias for about four days during the burn-in, thermal cycle, and QA. Fig. 6 shows the optical power of two boards measured at weekly intervals. The optical power is stable over time. The test is obviously stressful as evident in the darkening of the PCB and encapsulent as shown in Fig. 7. Given that the boards have survived significantly longer than the 1,000 hours as required in the optical industry, we are optimistic that the opto-boards will be fully operational for the next ten years.

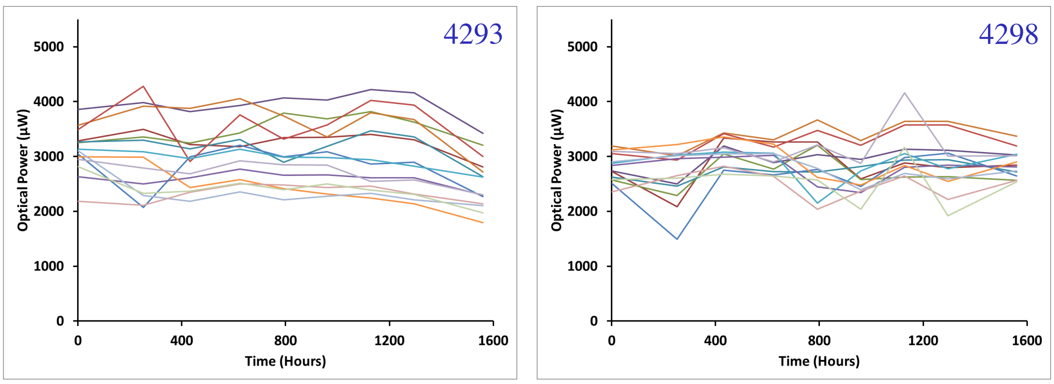

Figure 6: Optical power of two opto-boards as a function of time in a chamber operated at 85 C and 85% relative humidity. Each opto-board contains 14 VCSEL channels.

6. Conclusion

We presented the design, production, and a reliability study of the new opto-boards for the ATLAS pixel detector, including the insertable barrel layer (IBL). We also presented several improvements in the design which benefited from the production and operational experience of the first generation opto-boards. The new opto-boards have been successfully installed. A sample of the new opto-boards have been subjected to an accelerated lifetime test at 85 C and 85% relative humidity. No failures have been observed. We are cautiously optimistic that the opto-boards will survive until the shutdown for the detector upgrade for the HL-LHC program.

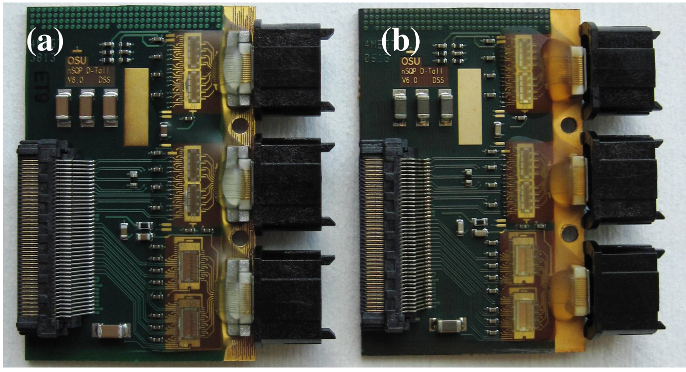

Figure 7: Comparison of an unexposed opto-board (a) vs. an opto-board that has been exposed to an environment of 85 C and 85% relative humidity for 1,500 hours.

Acknowledgments

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[2] K. Arms et al., ATLAS Pixel Opto-Electronics, *Nucl. Instrum. Methods*. A **554** (2005) 458.

[3] The PIN array used is ULM850-10-TN-N0112U, fabricated by ULM Photonics.

[4] The VCSEL array used is V850-2093-001, fabricated by Finisar, Inc.