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The cryogenic performances of specific optical and electrical components for a liquid argon time projection chamber

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Abstract

In this paper we present the cryogenic performance study of specific optical and electrical components for the Liquid Argon Time Projection Chamber (LArTPC), a potential far site detector technology of the long baseline neutrino experiment (LBNE). We have confirmed that an LVDS driver can drive a 20-meter CAT5E twisted pair up to 1 gigabit per second at liquid nitrogen temperature (77 K). We have verified that a 16:1 serializer Application Specific Integrated Circuit (ASIC), three types of laser diodes, optical fibers and connectors, and field-programming gate arrays (FPGAs) continue to function at 77 K. A variety of commercial resistors and capacitors have been tested at 77 K. All tests we have conducted show that the cold front-end electronics is promising.

Keywords: Time projection Chambers (TPC); Optical detector readout concepts; Cryogenic Detectors;

1. Introduction

The Long-Baseline Neutrino Experiment (LBNE) is a proposed experiment to explore the interactions and transformations of a high-intensity neutrino beam by sending it from Fermi National Accelerator Laboratory (FNAL) 1300 kilometers through the earth to Homestake Mine in Lead, South Dakota [1]. The LArTPC has full 3-D event reconstruction capability with sub-millimeter position resolution, larger than

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90% electron-photon separation, and particle energy threshold as low as 1-2 MeV, making it an ideal neutrino physics detector [2]. Two LArTPC modules each of which has about 20-kton volume have been proposed as a potential far-site detector technology of LBNE. The increase of the input capacitance and the input equivalent noise makes it impossible to build a large fiducial volume detector with all preamplifiers located outside the cryostat at room temperature. Moreover, large amount of cables and feedthroughs increase cost, thermal load, the possibility of outgassing and leaks, and the failure rate. Therefore, a cold front-end electronics system has been chosen as the reference design of the LBNE LArTPC [3].

In the cold electronics system, all preamplifiers, shapers, analog to digital converters (ADCs), zero suppression system, digital buffers, data multiplexers, and cable drivers are mounted in the liquid argon cryostat. To develop a cold electronics system, it is essential that all components still function properly at liquid argon temperature. The ASICs including the preamplifiers, shapers, ADCs, zero suppression, and digital buffers are under development and the ASIC performances at cryogenic temperature are discussed elsewhere [3]. In this paper we will focus on the performances of data links, including multiplexers and cable drivers.

2. Cold electronics overview

Fig.1 is the block diagram of the cold electronics. The analog signal from a sense wire is integrated in a charge sensitive amplifier (CSA) and converted into a voltage signal. The voltage signal is filtered in a shaper and digitized into a digital signal in a 12-bit ADC sampling at 2 mega-samples per second. Following the ADC is the zero suppression and digital buffers. A 16-channel mixed signal front-end ASIC, including CSAs, shapers, ADCs, zero suppression, and buffers, is under development. The signals out of the eight mixed signal ASICs will be multiplexed in a 128-channel front-end mother board. The signals out of 30 front-end mother boards will be multiplexed and transmitted out of the cryostat in a mux/control board.

The data rate out of the LArTPC highly depends on where the LArTPC is located. The data rate of a LArTPC at 800 feet underground is about 240 Mbps per anode plane assembly (APA) including a safety factor of 20. In this situation, the data will be transmitted through electrical data links. If the LArTPC is located on the earth surface, the data rate will be as high as 2 gigabit per second (Gbps) per APA before considering any safety factor. In this situation, the data will be transmitted through optical data links. The distance of data links are no more than 20 meters for both electrical and optical links. Both the optical and electrical links are shown in Fig. 1, but only one of the technologies will be used in the end. For optical links, the links between a mother board and a mux/control board are still electrical. For either electrical or optical link, double or triple links rather than a single link may be used to improve the reliability.

For electrical links, a natural choice is to transmit Low-voltage differential signaling (LVDS) over twisted pairs like Catalog 5 (CAT5) or enhanced Catalog 5 (CAT5E). Though LVDS and twisted pairs have been used for a long time and a lot of experiences have been gained [4-6], it is not clear that 240 Mbps LVDS signals can be transmitted over 20 meters CAT5 or CAT5E twisted pairs at liquid argon temperature.

An optical link is more complex than an electrical link. An optical link on the transmitter side includes an encoder to provide a transition control protocol, parallel word boundary in serial data, and DC balance, a serializer to convert parallel data to serial data, a laser diode driver, a laser diode, an optical fiber and an optical connector. The questions to be answered include whether the components of optical links still function at liquid argon temperature.

Since liquid nitrogen (whose boiling point is 77 K) is much cheaper than liquid argon, in this paper all studies were conducted at liquid nitrogen temperature or the temperature from room temperature to 77 K.

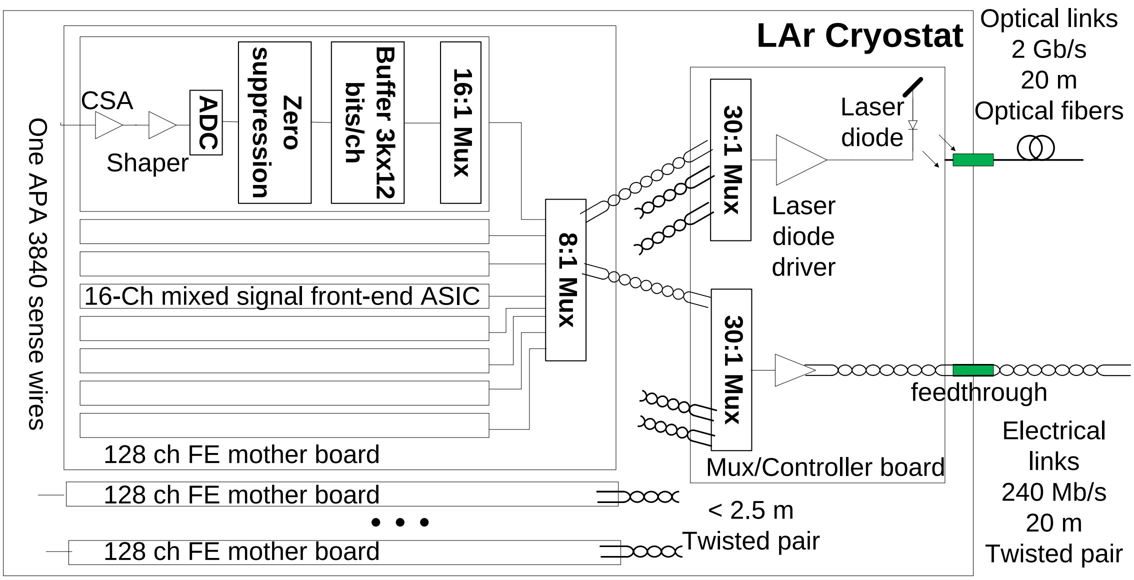

Fig. 1. The block diagram of the front-end electronics with optical data links

3. Cryogenic performance of electrical data links

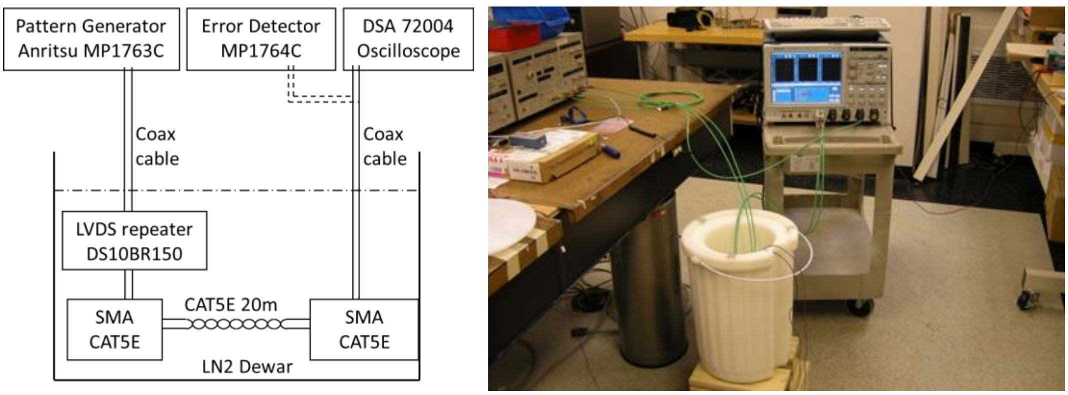

Fig. 2. (a) the block diagram of the test setup; (b) a picture of the test setup

For electrical data links, we tried to answer whether LVDS signals can be transmitted over 20-meters CAT5E twisted pairs at liquid argon temperature. We tested a commercial LVDS driver (part number DS10BR150 from National Semiconductor) and a 20-meter CAT5E twisted pair at liquid nitrogen temperature. Fig. 2(a) is the block diagram of the test setup. Fig. 2(b) is a picture of the test setup. The pseudorandom binary sequence (PRBS) data were generated in a pattern generator (Model MP1763C from Anritsu) and sent to the LVDS repeater. The output signals were sent to a real time oscilloscope (Model DSA72001 from Tektronix) to measure eye diagrams or an error detector (Model MP1764C from Anritsu) to measure the bit error rate (BER). At both ends of the CAT5E cable, we used a small printed circuit board (PCB) to connect the twisted pair to SMA connectors. The LVDS driver and the CAT5E cable were dipped in liquid nitrogen.

The eye diagrams at 1 Gbps at room temperature and at 77 K are shown in Fig. 3. The Eye opens wider at 77 K than at room temperature, indicating that the electrical link works better at 77 K than at room temperature. The bit error rate verified that the LVDS driver can drive 20-meter CAT5E twisted pair at the data rate up to 1 Gbps.

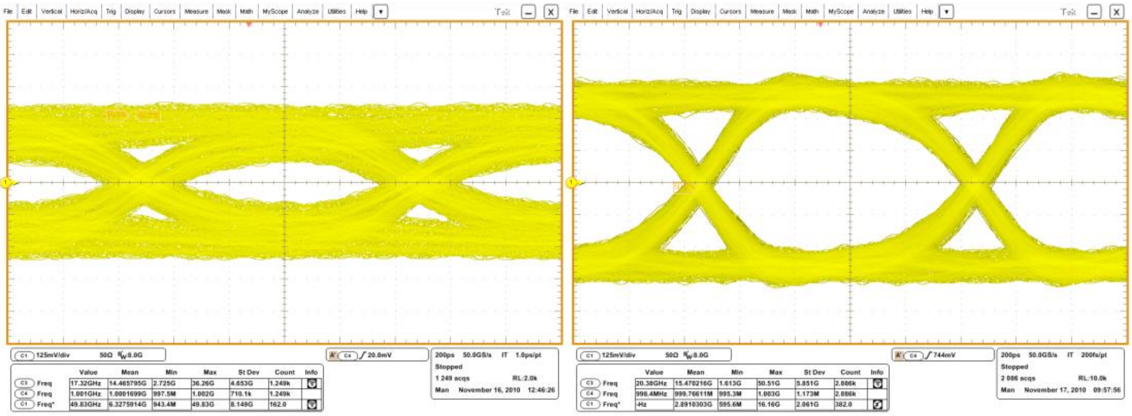

Fig. 3. (a) eye diagram at 1 Gbps and room temperature; (b) eye diagram at 1 Gbps and 77 K

4. Cryogenic performance of optical data links

For optical links, we tried to answer whether the components of optical links still function at liquid argon temperature. We have tested a 16:1 serializer Application Specific Integrated Circuit (ASIC) fabricated in a commercial 0.25-micrometer Silicon-on-Sapphire CMOS technology, three types of laser diodes, and multimode and single mode optical fibers and optical connectors [7].

4.1. Optical fibers and optical connectors

A single mode (SM) optical fiber (Part number SMF-28 from Corning) and a multimode (MM) optical fiber (Part number InfiniCor SX+ from Corning), five SM LC connectors (Part number F1-8005 from Fiber Instrument Sales, Inc.) and five MM LC connectors (Part number F1-8001 Fiber Instrument Sales, Inc.) have been tested from room temperature to 77 K. The insertion loss increases by 0.034 ± 0.015 dB/m and 0.005 ± 0.002 dB/m for MM and SM fibers, respectively. The insertion loss changes from room temperature to 77 K is 0.139 ± 0.020 dB per connector and -0.284 ± 0.014 dB per connector for MM and SM connectors, respectively. Given a usual optical power budget of around 10 dB in a link system, the small power loss in the fibers and connectors at 77 K can be easily accommodated.

4.2. Laser diodes

A vertical cavity surface emitting laser (VCSEL) diode, a distributed feedback (DFB) laser diode and a Fabry-Perot (FP) laser diode were tested from room temperature to liquid nitrogen temperature. The light power-current-voltage (L-I-V) characteristic curves and optical spectrum of each laser diode were measured throughout the test. All three types of laser diodes continue to function from room temperature to 77 K. The voltage thresholds of all three laser diodes increase from room temperature to 77 K. The current thresholds of the DFB and FP laser diodes decrease when temperature decreases from room temperature to 77 K, whereas the current threshold of the VCSEL increases. The light efficiencies of the VCSEL and the FP laser almost do not change at room temperature and 77 K, but the light efficiency of the DFB laser drops when the temperature is close to 77 K. In optical spectra, when the temperature changes from room temperature to 77 K, the center wavelength shifts toward the short wavelengths and the spectral width becomes narrow.

4.3. The serializer

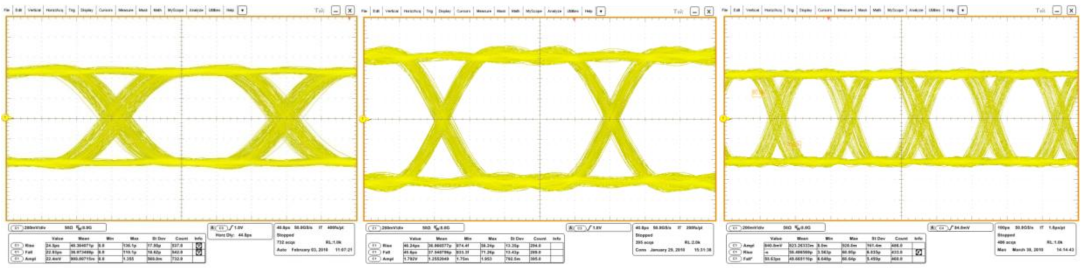

Fig. 4. (a) the eye diagram at room temperature and nominal voltage; (b) the eye diagram at 77 K and nominal voltage; (c) the eye diagram at 77 K and 1.8 V

A high speed 16:1 serializer application-specific-integrated-circuit (ASIC) [8] fabricated in a commercial 0.25-μm silicon-on-sapphire CMOS technology was tested at liquid nitrogen temperature. The eye diagrams of the serializer at room temperature and at 77 K are shown in Fig. 4. The serializer has wider eye opening, faster transient time, smaller jitter and larger amplitude at 77 K than at room temperature. Due to hot carrier effects, chip reliability might be reduced at cryogenic temperature [9]. Low power supply voltage may mitigate the hot carrier effects and hence increase its reliability. The eye diagram shown in Fig. 4(c) is the output of the serializer operating at 1.8 V. The nominal power supply voltage is 2.5 V. It is possible to improve the reliability at cryogenic temperature by operating the serializer at a lower power supply voltage.

5. Cryogenic performance of FPGAs

The approach to use commercial off the shelf (COTS) devices are much cheaper and faster than the ASIC development approach. The digital multiplexers and cable drivers can be implemented in an FPGA. The lifetime of FPGAs may be an issue and needs to be verified. However, while the digital logic ASIC is still not ready, an FPGA can be used temporarily for the proof of concept. Here we report the functionality test of FPGAs.

An FPGA, EP2SGX90 in Stratix II GX series from Altera was tested at 77 K. With a clock input at 156 MHz, a 2^{23}-1 PRBS generator is implemented at 5 Gbps inside the FPGA. The eye diagrams at room temperature (a) and at 77 K (b) are shown in Fig. 5. The FPGA continues to function at 77 K.

Several FPGAs in Cyclone II series from Altera were tested at 77 K. A PRBS generator, a ring oscillator based on 17 stages of NOT gates, and a phase clocked loop (PLL) were implemented. For the PRBS generator, the eye diagram was measured. The bit error rate was measured with no error during the test. For the ring oscillator, the differential amplitude, rise time and fall time, and power supply current were measured. For the PLL, the tuning range and jitter were measured. All measured parameters fell into the ranges specified in the data sheet.

The configuration memory EPCS4 from Altera was tested at 77 K. FPGAs can be programmed using configuration memory correctly at 77 K.

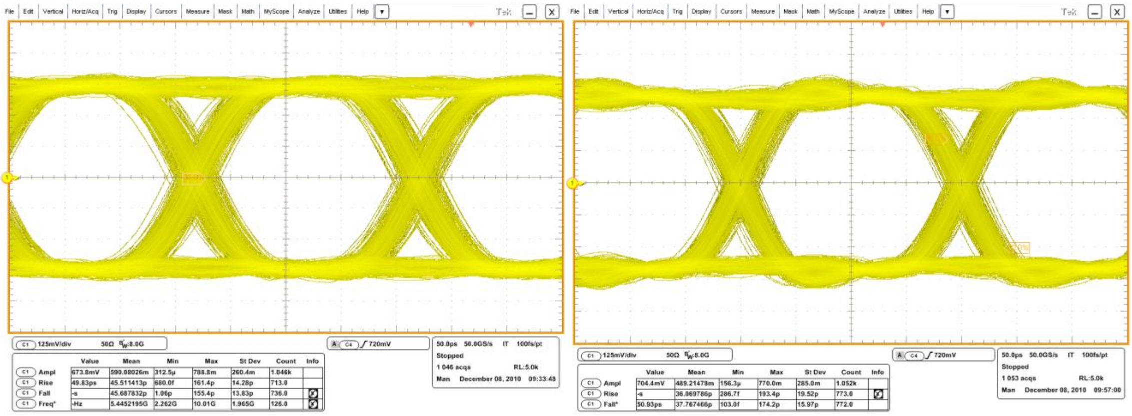

Fig. 5. (a) eye diagram at room temperature; (b) eye diagram at 77 K;

6. Cryogenic performance of passive components

Table 1. Parameter change from room temperature to 77 K

Type	Parameter change from room temperature to 77 K (%)
Metal Element resistors	-6.59
Carbon Composition resistors	19.10
Carbon Film resistors	6.40
Thin Film resistors	-0.21
Metal Film resistors	0.08
Wire wound resistors	0.15
Thick Film resistors	3.48
Aluminum electrolytic capacitors	-100%
NbO electrolytic capacitors	-71% ~ -39%
Tantalum Electrolytic capacitors	-47% ~ -10%
C0G/NP0 ceramic capacitors	-4.1% ~ 0.35%
U, X, Y, Z ceramic capacitors	-24% ~ 94%
Film capacitors	-13% ~ 3.8%
Mica capacitors	-0.35% ~ -0.12%

Passive devices like resistors and capacitors are essential components for cold front-end electronics. For example, the decoupling and AC coupling capacitors from the wires to pre-amplifiers must be in liquid argon. The operation of resistors and capacitors in cryogenic temperature has been reported in literatures with a lot of non-consistence [10-13]. To study the performance of passive components, we purchased all types of resistors and capacitors available at the market and measured the parameters at room temperature before they are dipped into liquid nitrogen, when dipped in the liquid, 20 minutes after being taken out of liquid nitrogen, and when dipped in the liquid again. At each condition, we measured at

100 Hz, 1 kHz, and 100 kHz with an LCR meter (Model 720 from Stanford Research System). For most resistors and capacitors (except electrolytic capacitors), the difference between frequencies is small.

The parameter changes at 1 kHz from room temperature to 77 K are listed in Table 1. At 77 K, the resistance of the carbon composition resistors increase 19% and the resistance of metal element, wire wound, carbon film, thin film, metal film, and thick film change less than 7%. Capacitance of tantalum Electrolytic, C0G ceramic, film and mica capacitors change less significantly than that of aluminium electrolytic, niobium oxide electrolytic capacitors, U, X, Y, Z ceramic capacitors. Resistance and capacitance in the two measurements at 77 K change about (only metal element resistors) or less than 1% (all other resistors and capacitors), meaning the measurements at 77 K are repeatable.

7. Conclusion

We have studied the cryogenic performances of an LVDS driver driving 20-meter CAT5E twisted-pair, a 16:1 serializer ASIC, laser diodes, optical fibers, and optical connectors, FPGAs, resistors and capacitors. All tests conducted show that the cold front-end electronics is promising.

The performance of some components (e.g., laser diode drivers) has not been studied yet. After the cryogenic functionality on component level, another important issue is the reliability. Since the cold electronics system has little or no access for repair or replacement after installation, the lifetime of all components operating in the LArTPC must be more than the design lifetime of the LArTPC or 20 years. Though most of failure modes improve at cold temperature, the failure mode induced by hot carrier effects becomes worse at cryogenic temperature than at room temperature [9]. We are studying the reliability of the cold electronics components and will report it in the future.

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