

# Optical Data Links in CMS ECAL

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## Abstract

The CMS ECAL will employ approximately 10,000 digital fiber-optic data links. The Data Link System is responsible for receiving and serializing 16 bit-streams of data at 40 MHz; encoding with either 8-bit/10-bit or G-Link protocol; transmitting via optical fiber; and finally, converting the data back to a serialized, encoded 800 Mb/s electrical stream. The technologies chosen include the GOL ASIC; edge-emitting laser diodes and opto-receivers operating at 1310 nm and from  $-18$  dBm to  $-6$  dBm; and single-mode optical fiber and connectors. Environmental, reliability and performance characteristics of system components have been extensively qualified. The Data Link as a whole is characterized by clean eye diagrams; end-to-end jitter  $< 50$  ps; measured and estimated Bit Error Rates of  $< 2 \cdot 10^{-15}$  and  $< 10^{-16}$ , respectively; and an optical power budget margin of 6 dB under the least-favorable combination of foreseen circumstances.

## I. INTRODUCTION

The CMS [1] ECAL [2] Optical Data Link System [3] will employ approximately 10,000 digital fiber-optic data links to transport data and trigger primitives off-detector. The system is responsible for receiving and serializing 16 bit-streams of data at 40 MHz from a Front End System card; encoding with either 8-bit/10-bit or G-Link protocol; transmitting the data via optical fiber at 800 Mb/s; and finally converting the data back to a serialized and encoded 800 Mb/s electrical stream and transmitting it to an Off Detector System card.

## II. OPTICAL TRANSMITTER

The optical transmitter of the Data Link System is the custom-built GOL Opto-Hybrid (GOH) [4], a  $25 \times 32$  mm<sup>2</sup> card containing the GOL serializer and laser driver ASIC [5] and a 1310 nm edge-emitting laser diode [6] [7]. Optical transmission occurs via a single-mode pigtail fiber aligned to the laser diode and bonded to the package. An FR4 fiber-clamp provides strain relief of the fiber. The downstream end of the fiber is terminated in a MU connector [8]. A photograph of the GOH is shown in Figure 1.

The GOH receives power, clock and control, and 16-bit parallel digital data signals from the Front End card. The

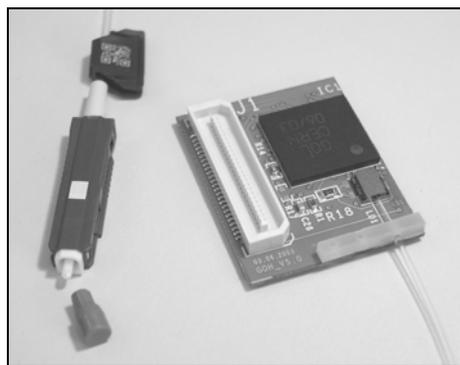


Figure 1. The GOL Opto-Hybrid (GOH).

clock input is LVDS, while control and data are LVCMOS (2.5 V) levels. Control inputs allow to reset the GOL; to select GOL output protocol; to select laser diode bias currents; to power-cycle the GOH; etc. The power-cycle feature is achieved using the CRT4T [9] [10] [11], a CMOS power-switching chip developed by the CERN Microelectronics Group.

### A. The GOL ASIC

The GOL serializer and laser driver ASIC [5] was designed by the CERN Microelectronics Group. The die is produced by IBM. The  $13 \times 13$  mm<sup>2</sup> fpBGA packaging is performed by Atlantic.

The GOL is implemented in 0.25  $\mu$ m CMOS technology employing radiation-tolerant layout practices. It is designed to prevent or recover from Single Event Upsets (SEU) with minimal impact on the data. Some configuration data is hard-wired to input pins. All other configuration data is stored in Hamming-code protected registers. Finally, triple-redundant voting logic is employed.

The GOL is capable of taking either 16- or 32-bit parallel data input at 40 MHz. The additional overhead bits required for encoding result in output serial data rates of 800 or 1,600 Mb/s. The CMS ECAL employs only the 800 Mb/s rate.

The GOL is capable of transmitting in either 8-bit/10-bit or G-Link protocols. The CMS ECAL uses both: the deserializer-encoded Xilinx FPGA on the Data Concentrator Card requires 8-bit/10-bit, while the Agilent HDMP-1034A deserializer chip on the Trigger Concentrator Card requires G-Link.

## B. The ST Laser Diode

The ST laser diode [6] [7] consists of a Mitsubishi 1310 nm edge-emitting laser diode die [12] housed in a custom-built 4.5 x 4.0 x 1.5 mm<sup>3</sup> laser-pill package, developed and assembled by ST Microelectronics. It was originally developed for CMS Tracker Optical Links [6]. The laser diode has a rise time of 0.3 ns, consistent with use in 800 Mb/s digital operation. Its output power<sup>1</sup> of up to 0 dBm is more than sufficient for the Data Link receiver. It has a threshold current of 5 mA, a forward bias voltage of 1.2 V, and a slope efficiency<sup>2</sup> of 40  $\mu$ W/mA.

## C. GOH performance

The GOH delivers a clean eye diagram when driven with a bias current of 14 mA at 800 Mb/s, as shown in Figure 2. At this current, the optical power output from the MU connector is approximately -6 dBm. The RMS jitter is measured to be less than 20 ps.

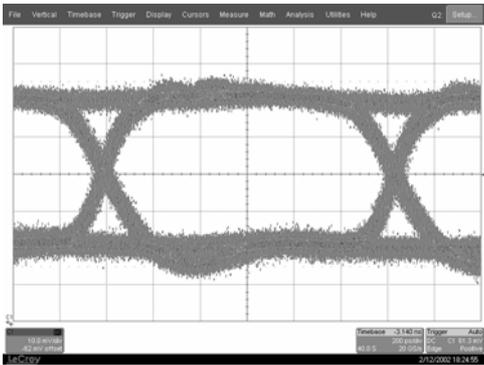


Figure 2. GOH eye diagram.

## III. OPTO-RECEIVER

The opto-receiver employed is the 12-channel digital Rx module POR10M12SFP [13] produced by NGK. It accepts single-mode, 12-fiber ribbon via an MPO receptacle. It is mounted on the Off Detector card and transmits 12-channel serial data at 800 Mb/s per channel to the deserializers.

The operating wavelength of the receiver is 1310 nm. Its speed is rated up to 1.25 Gb/s. Its saturation input power level is -5 dBm. Its sensitivity level extends down to -18 dBm. The RMS jitter is measured to be less than 42 ps. These characteristics are all consistent with use with the GOH.

## IV. OPTICAL FIBER SYSTEM

### A. Fiber, Connectors and Adaptors

The optical fiber employed is single-mode 9/125  $\mu$ m, manufactured by Ericsson from Corning pre-forms.

The fiber chain begins with the GOH pigtail of tight-buffered 0.9 mm single fiber [14]. The MU<sup>3</sup> [8] connectors of up to 12 GOH are inserted into a 12-channel MU-SR [15] adaptor. On the opposite end is a fanout [16] (serving as a fan-in), which merges individual fibers into a sheathed 12-fiber ribbon [17]. The individual fibers are terminated in sMU [15] (MU-simplified) connectors; the ribbon is terminated in an MF-A2 [18] connector based on an MT ferrule.

The MF-A2 connectors of up to 8 fanouts are inserted into a duplex MF-B2/B3 adaptor [18]. On the opposite end is a dense multi-ribbon (“trunk”) cable, which contains 8 ribbons in a loose-tube configuration. The individual naked ribbons are broken out at both ends of the trunk cable. On the MF-B2/B3 end they are terminated in MF-B1 connectors based on an MT ferrule. On the opposite end they are terminated in MPO<sup>4</sup> [19] connectors based on an MT ferrule.

The tight-buffered single fiber, fiber ribbon and trunk cable are all manufactured by Ericsson. The MU and sMU terminations as well as the fanout to individual fibers are performed by Sumitomo Electric Industries. The breakout, MF-A2, MF-B1 and MPO terminations are performed by Diamond.

The insertion loss (optical power loss) at each connector interface is measured to be typically 0.6 dB, with a specification maximum of 1.2 dB.

### B. Optical Fiber Implementation

The fiber chain is illustrated in Figure 3.

The MU-SR adaptor is housed in an aluminum box within the ECAL volume, which forms the Distributed Patch Panel. The MF-B2/B3 adaptor is housed in a second aluminum box at the periphery of the ECAL, which forms the In-Line Patch Panel. Both patch panels house excess slack fiber and protect the naked parts of the ribbons.

In front of the Off Detector card an aluminum Back-End Patch Panel protects the naked parts of the ribbons and routes them to the receiver modules. Only the extremely rugged trunk cable is exposed in the fully assembled ECAL.

## V. ENVIRONMENTAL AND RELIABILITY SPECIFICATIONS

All materials employed meet stringent low-smoke-zero-halogen [20] and non-magnetic materials requirements.

All Data Link components except the receiver are extensively qualified for radiation-resistance ( $10^{14}$  p/cm<sup>2</sup> and  $10^5$  Gy). Laser diode die wafer lots are radiation-qualified with gammas and neutrons [21] before assembly into laser diodes. Intensive irradiation increases the threshold current; however the long-term effect is small due to the substantial

<sup>1</sup> A logarithmic scale of absolute optical power: 0 dBm = 1 mW

<sup>2</sup> Slope efficiency is selected in the ST bonding process by varying distance between diode and fiber. Similar laser diodes for control links of CMS Tracker and ECAL have a slope efficiency of 10  $\mu$ W/mA.

<sup>3</sup> MU-UPC (Ultra Physical Contact)

<sup>4</sup> MPO-APC (Angled Physical Contact)

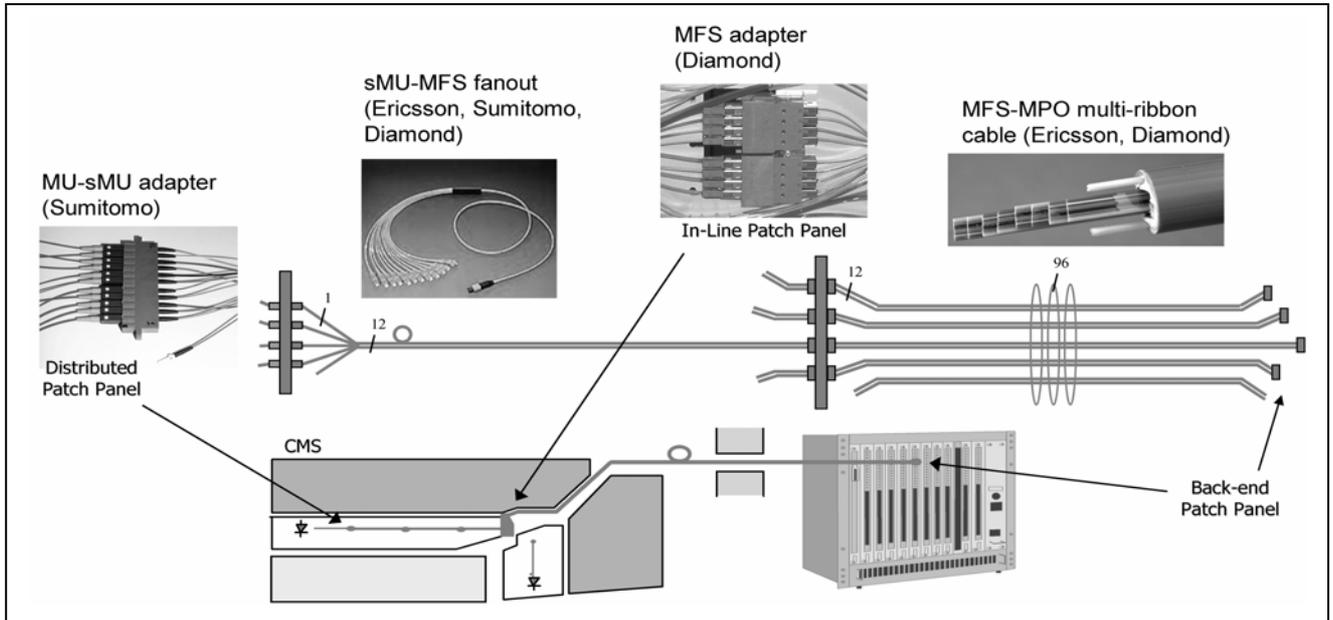


Figure 3. The CMS ECAL Data Link optical fiber system.

annealing of the laser, even at  $-20^{\circ}\text{C}$ . Fiber attenuation is negligible even after intensive irradiation [22].

The buffered single-fiber is qualified for ambient operating temperatures from  $-20^{\circ}\text{C}$  to  $+40^{\circ}\text{C}$ . The receiver is qualified from  $+18^{\circ}\text{C}$  to  $+80^{\circ}\text{C}$ . All other Data Link components are qualified from  $-20^{\circ}\text{C}$  to  $+60^{\circ}\text{C}$ .

Most Data Link components will be inaccessible and therefore required to operate with perfect reliability throughout their expected operating life of 10 years. Towards this end all GOH are operated under power for 72 hours at  $40^{\circ}\text{C}$  before installation, to remove infant mortality.

## VI. SYSTEM TESTS AND PERFORMANCE

The Data Link system as a whole is qualified using two different setups. The first is a Bit Error Rate Test (BERT) system, which is used to measure an upper limit on the BER while the Data Link is operated under ideal laboratory conditions. The second is a Word Error Rate Test (WERT) system, which is used to measure the degradation in performance of the Data Link when a stress is applied to the system.

### A. The Bit Error Rate Test system

The BERT is a custom-built system based on GIII [23] [24] Tx and Rx PCI cards developed by the CMS DAQ group. It is illustrated in Figure 4. The GIII cards are controlled by a LabVIEW program via the PCI interface of a PC. The GOH, receiver and an appropriate deserializer<sup>5</sup> are assembled on their respective evaluation boards and connected. A PCI I2C interface is used to control GOH configuration parameters such as the laser diode bias current. Altera FPGA's on the Tx

and Rx cards generate data input to the GOH and read output from the deserializer, respectively, via S-Link [25] [26] interfaces. Tx and Rx data are transferred to PC memory via the PCI bus and compared. The comparison is bit-by-bit, independent of serializer protocol. Due to PCI limitations the duty cycle is limited to about 40%: with the Data Link driven at 800 Mb/s, the BERT is able to compare about 300 Mb/s.

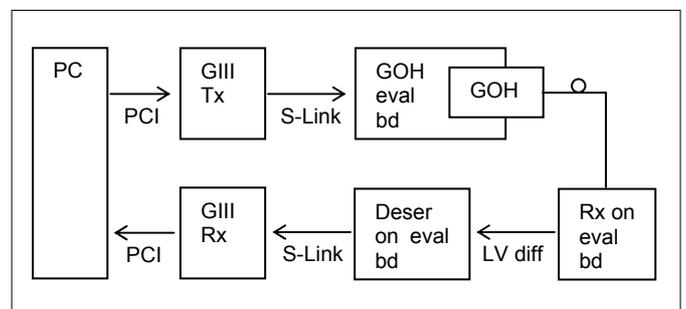


Figure 4. Diagram of the BERT system.

Using the BERT, the bit error rate has been measured to be less than  $2 \cdot 10^{-15}$ . Spurious errors generated by resource usage by the operating system do not allow to measure a BER lower than this, although the actual BER of the Data Link system may be significantly lower. It is useful therefore to have another measure. A simple, standard calculation [27] allows one to estimate the BER from the signal-to-noise ratio of the eye diagram:

$$BER_{TH} = \frac{1}{2} \operatorname{erfc} \left( \frac{(S/N)^{1/2}}{2\sqrt{2}} \right)$$

From this, a BER of less than  $10^{-16}$  is estimated even when the input to the receiver is attenuated to  $-18$  dBm, the sensitivity threshold.

<sup>5</sup> In the case of 8-bit/10-bit, the TI TLK1501 is employed; in the case of G-Link it is the Agilent HDMP-1034A.

### B. The Word Error Rate Test system

The Word Error Rate Test system is a simplified version of the BERT system. It is illustrated in Figure 5. Like the BERT, it contains the GOH, receiver and deserializer assembled on their respective evaluation boards and connected. However, in the WERT, the signals to drive the GOH are generated by the Altera FPGA on the GOH evaluation board itself. A clock generator synchronizes the Altera and the deserializer. The WER is determined by counting word errors (frame errors) flagged by the deserializer.

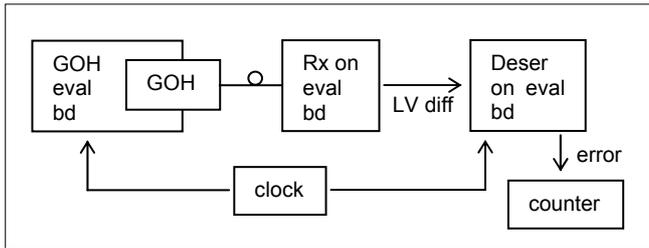


Figure 5. Diagram of the WERT system.

The WERT is used to measure the degradation in performance of the Data Link when a stress is applied to the system, in the following fashion: A variable optical attenuator is inserted after the GOH, and the WER is plotted as a function of optical power input to the receiver. The stress is applied to the system and the measurements are repeated. This is illustrated in Figure 6. The shift in the WER curve represents the additional power required to compensate for the stress, and it is therefore considered as the penalty on the optical power budget introduced by the stress.

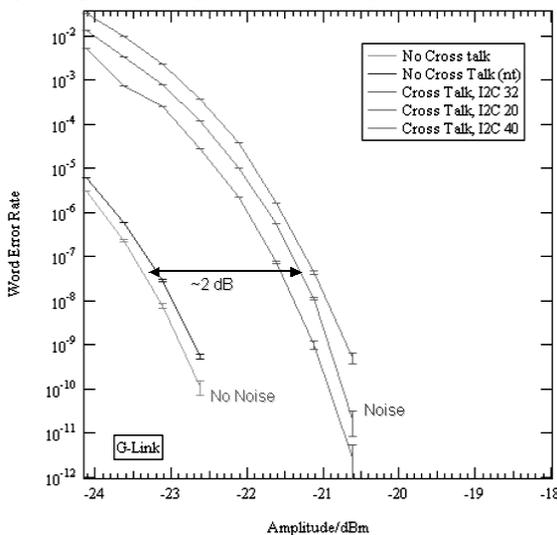


Figure 6. WER vs. optical power at the receiver, for tests with and without noise data on adjacent channels.

The power budget penalty in the presence of more than one stress is considered to be the sum of the individual penalties. For this to be valid, it is necessary to assume that the effects add linearly. For “small” enough stresses this should be a reasonable assumption.

### C. Data Link System Tests

Figure 6 illustrates the effect of crosstalk in the receiver, using the WERT system. When adjacent channels are driven with noise data, a penalty of 2 dB is evident on the optical power budget.

Figure 7 illustrates the effect of increasing the ambient temperature around the receiver, using the WERT system. There is no significant effect up to +80°C, and therefore no penalty on the optical power budget. A similar study shows no penalty on the power budget for GOH ambient operating temperatures up to +60°C.

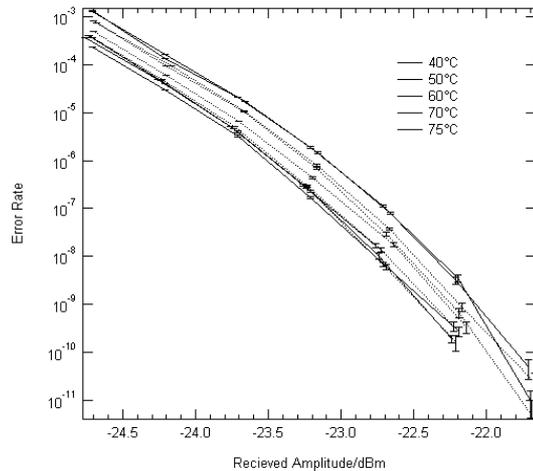


Figure 7. WER vs. optical power at the receiver for varying ambient receiver temperature.

The RMS jitter of the Data Link is measured to be less than 50 ps end-to-end.

The effect of irradiation on GOH performance was tested using the BERT system. One GOH was operated normally in the BERT while being exposed to  $8 \cdot 10^{13}$  protons/cm<sup>2</sup> over a 24-hour period at the 60 MeV OPTIS beam [28] at PSI. Nine other GOH were simultaneously irradiated in an adjacent stack farther down the beam line while being driven with an idle pattern. They were not connected to the BERT but shared the same I2C line as the BERT GOH. The irradiated GOH stack is shown in Figure 8.

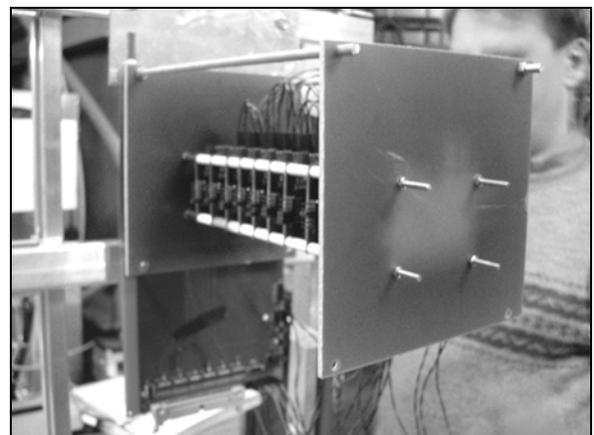


Figure 8. The GOH stack after irradiation.

The 0 and 1 optical power output levels of each GOH were measured at regular intervals for three different laser diode bias currents. Figure 9 shows a plot of the power levels for the fourth GOH in the non-BERT stack. Several features are evident. First, the power output declines steadily as the threshold current increases with dose. Second, the separation of the 0 and 1 levels (the height of the eye diagram) remains essentially constant, so long as the 0 level remains above threshold. (This also implies that the slope efficiency remains constant.) Third, these observations are true for a wide range of bias settings. The practical implication of these observations is that it would be possible to compensate for radiation damage to the lasers by steadily increasing the bias current over the life of the experiment, with no consequence on the optical power budget, even if the lasers did not benefit as they do from substantial annealing.

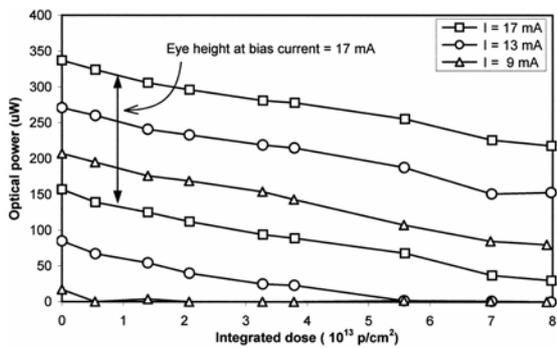


Figure 9. Evolution of GOH 0 and 1 output power levels as a function of proton dose.

The BERT GOH experienced five errors over the course of the study, all of which occurred when the shared I2C line was accessed to control other GOH. These may be interpreted as spurious, or in the worst case suggest a Single Event Upset rate of up to about five events over the life of the experiment.

No GOH died or had any lasting effect as a consequence of the irradiation.

#### D. Integration with Front End and Off Detector Systems

The Data Link has been tested with a prototype of the Front End system during the summer 2003 ECAL testbeam program. It has been tested in October 2004 with final versions of the Front End card and the Data Concentrator Card. No errors were attributed to the Data Link System during these tests.

#### E. Optical Power Budget

A power of  $-6$  dBm is launched from the GOH. A penalty of 1 dB is taken due to the allowed variation of up to 10% in the slope efficiency from laser to laser (no attempt is made to compensate for this by adjusting bias levels, although this could be done to remove the penalty). A penalty of 3 dB is taken to allow for losses at connector interfaces. Finally, a penalty of 2 dB accounts for the effect of crosstalk in the receiver, as described above. The effective optical signal power at the input to the receiver is therefore  $-12$  dBm. This

is to be compared with the receiver sensitivity limit of  $-18$  dBm. The Data Link therefore has at least 6 dB of optical power budget margin under the least-favorable combination of foreseen circumstances.

## VII. CONCLUSIONS

An Optical Data Link has been developed for CMS ECAL which meets the various requirements. It performs serialization, encoding and transport of data at the required rate of 800 Mb/s using either 8-bit/10-bit or G-Link protocols. It is tolerant to its environmental specifications of temperature and irradiation. It has clean eye diagrams, low bit error rate and low jitter. Finally, it has ample optical power budget margin.

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