Qualification of the CMS Tracker Control Link Digital Optohybrid

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Abstract

The transfer of CMS Tracker timing, trigger and control signals over an optical link network relies on the robustness and reliability of its constituent parts. The front-end digital optohybrid (DOH) required a thorough evaluation prior to the launch of its full production phase. Pre-production DOHs were put through a well-defined qualification programme involving visual inspection, optical, electrical, radiation, magnetic field, temperature cycling, shock, vibration and pull tests to evaluate quality, functionality and strength against environmental and handling stresses.

I. INTRODUCTION

The CMS Tracker will employ digital optical links [1] in the communication chain to control front-end detector elements. The digital optical control links are bi-directional: the transmission of the LHC clock and CMS level-1 trigger at 80 Mbit/s as well as control signals at 40 Mbit/s occurs in one direction, from the front-end controller cards (FECs) located in the counting room to the front-end communication and control units (CCUs); the transmission of status data and clock signals occurs in the other direction, from the front- to the back-end. The digital optohybrid (DOH), located at the front-end, is the interface between the digital optical control link system and the electrical CCUs (Fig. 1).

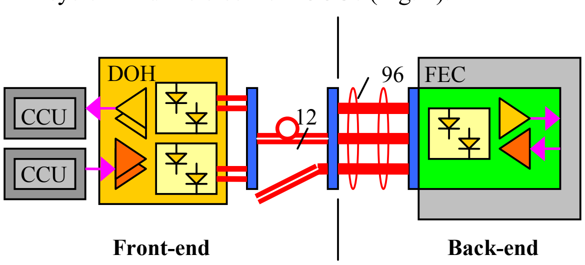

Figure 1: CMS Tracker digital control links

There are two basic versions of the DOH: DOH 056 and DOH 200 [2]. The first version (~80% of DOHs) has 56 cm fibre pigtails and the second version (~20% of DOHs) has 200 cm fibre pigtails. The DOH was designed for the CMS Tracker and has now been adopted by other sub-detector systems (Table 1). For the Pixel system there will be a modification of the DOH 200 with a different photodiode-receiver ASIC.

Table 1: Breakdown of DOH numbers per sub-detector

CMS Sub-detector	Number of DOHs
Pixels	128
Tracker	700
ECAL	736
Preshower	104
RPCs	28
Total	1696

To reduce the link development effort, components for the digital optical control links are derived wherever possible from the much larger analogue optical readout system, which has ~40000 channels. The optical control links system shares laser-driver ASICs (LLD), lasers, fibres and connectors with the optical readout system. Only the photodiodes and the photodiode-receiver ASICs (RX40) used in the detection of optical signals at the front-end are specific to the control links.

The CMS Tracker environment is characterised by high levels of radiation, up to ~2 x 10^{14} cm^{-2} fluence and 100 kGy ionizing dose, a 4 T magnetic field and –10^{o}C temperature over 10 years of operation [3]. The harshness of this environment is compounded by the inaccessibility of the detector for repair.

The main electrical components of the DOH, the LLD and the RX40, are custom-made radiation-tolerant components. The optical components of the DOH, which include InGaAsP/InP multi-quantum-well edge-emitting lasers, InGaAs p-i-n photodiodes, single-mode buffered fibres and MU-type connectors, are either commercial off-the-shelf (COTS) components or components based on COTS. An extensive series of sample tests was carried out to evaluate the feasibility of an optical link based on such COTS components, to determine the link specifications, and to select suitable components [4].

The standard qualification procedures typically adopted by manufacturers do not cover the special requirements of the CMS Tracker environment. For this reason, quality assurance (QA) procedures were defined for all optical components. These QA procedures call for thorough testing of components to guarantee their good functionality over the lifetime of the CMS experiment.

A qualification procedure was defined for the DOH as a whole in addition to the QA procedures that exist for its discrete components [5]. This paper presents data on the full DOH pre-production qualification programme, including visual inspection results, geometrical measurements, optical, electrical, temperature cycling, magnetic field, radiation, shock, vibration and pull-test results.

II. PRE-PRODUCTION SAMPLE HISTORY

The assembly of DOHs is carried out by Kapsch Components KG (Vienna), which has extensive experience in handling optohybrids since it assembles a large fraction of the readout link analogue optohybrids (AOH). Kapsch procures the DOH PCBs, onto which it then mounts SMD components, solders photodiodes, glues and bonds lasers and finally glues fibre clamps and laser covers.

A pre-production batch of 40 DOHs produced by Kapsch was received at CERN in March 2004. This batch consisted of DOH 056 with two types of fibre clamp: 20 DOHs had CERN fibre clamps and 20 DOHs had Kapsch fibre clamps, similar to those used on the AOH (Fig. 2). The fibre clamps are meant to provide additional strain relief to the fibres. One of the objectives of the first pre-production batch was to select the best fibre clamp design. Although the functionality of the DOHs was fine, the qualification was failed due to various assembly problems, the most serious being fibre buffer ruptures. These problems are discussed in section IV of this paper.

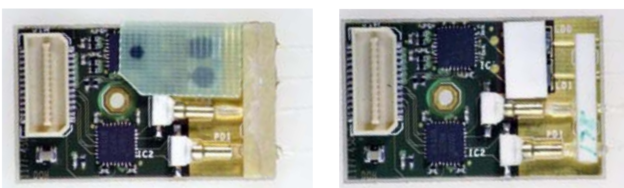

Figure 2: DOH types from first pre-production run, CERN fibre clamp (left) and Kapsch fibre clamp (right)

Following some recommendations made to Kapsch in April 2004 and a redesign of the CERN fibre clamp, a second pre-production batch of 37 DOHs was manufactured and received at CERN in June 2004 (Fig. 3). This batch contained a mix of DOH 056 and DOH 200, all with the redesigned CERN fibre clamp, in order for Kapsch to experience handling the 200 cm fibre pigtails.

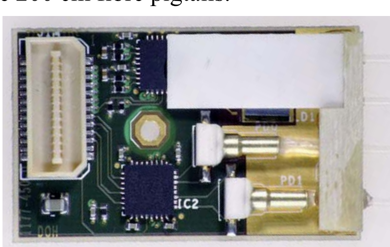

Figure 3: DOH from second pre-production run

III. QUALIFICATION PROGRAMME

Each optical component on the DOH has gone through its own QA programme [6]. The first step in the QA programme was the technical qualification of suppliers in the framework of CERN market surveys. Market surveys for lasers and connectors were issued in 1999 and those for optical fibres were issued in 2000. Manufacturers that were successful at this stage were invited to tender for the production of the final components.

The following step was the pre-production qualification, necessary to qualify the devices and manufacturing processes in preparation for full production. One key element in the QA programme, which occured in parallel with the pre-production qualification, was the advance validation test (AVT) where a small sample from every batch of components (e.g. 20 lasers from a wafer of ~8000 lasers) was subjected to rigorous environmental testing. This ensured that batch-to-batch variations of radiation hardness and reliability were closely monitored and entire batches were not rejected at later assembly stages due to non-compliance with the CMS Tracker environment.

Upon satisfactory qualification of a pre-production batch, full production was initiated. The quality of production batches was monitored through lot validation tests on small samples taken at random from each production batch.

This paper is concerned primarily with the pre-production qualification of the DOH. A well-defined procedure was established to undertake this step in the quality assurance of the DOH. All DOHs from the pre-production batch were inspected visually for defects. They were then measured geometrically. Following these measurements of the DOHs' physical characteristics, optical and electrical tests were carried out on a custom test bench to determine their functionality. A whole series of environmental tests was then applied to samples of varying numbers of DOHs (Table 2).

Table 2: Size of DOH samples used in qualification

Test Procedure		Pre-production Batch 1	Pre-production Batch 2
1	Visual Inspection	40 DOH (100%)	37 DOH (100%)
2	Geometrical measurement	40 DOH (100%)	37 DOH (100%)
3	Optical/Electrical test	40 DOH (100%)	37 DOH (100%)
4	Magnetic field test	2 DOH (5%)	
5	Irradiation test	6 DOH (15%)	
6	Thermal Tests	6 DOH (15%)	20 DOH (54%)
7	Non-destructive fibre pull test	5 DOH (12%)	4 DOH (11%)
8	Optical/Electrical test	Re-test DOH from Tests 4, 5, 6 & 7	Re-test DOH from Tests 6, 7
9	Destructive fibre pull test	5 DOH (3 from Test 7)	4 DOH (11%)
10	Bond pull test	Done on series production PCBs	
11	Mechanical shock	6 DOH (15%)	
12	Optical/Electrical test	Re-test DOH from Test 11	

IV. ASSEMBLY QUALITY

A. Visual Inspection

The visual inspection included a check of the visible quality of the fibres, connectors, solder joints, all glue joints and all sub-components in terms of their placement and alignment. The general quality of the first pre-production batch of DOHs was disappointing. Many defects relating directly to the assembly of the DOHs were identified. The most important of these were buffer ruptures on the optical fibres and the gluing or positioning of the fibre clamp. Because of these quality defects, the first pre-production batch was rejected. Examples are listed here for DOHs with the Kapsch fibre clamp (Table 3).

Table 3: Visual inspection results for DOHs with the Kapsch fibre clamp

Inspection Tests	# Pass	# Fail	Comments
ASICS, LDs and PDs	18	2	Photodiode PD1 ferrules pushed too firmly onto DOH, possibly breaking the fibre on the known non-functional DOH (2)
Fibre clamp	12	8	Fibre clamp not covering PD1 (1) Insufficient glue used (7)
Laser cover	0	20	Ceramic cover glued onto lasers
QR code	18	2	Not enough glue used (1) AOH code found (1)
Gluing	17	3	Excess glue beyond PCB edge (1) Insufficient glue in fibre clamp (2)
Soldering	8	12	Excess solder flux on PCB (12) Suspected dry solder joint on photodiode (1 piece, same board also warped near NaiS)
Fibre and connector	19	1	Buffer rupture near PCB on PD0 (1)

A second pre-production batch of 37 DOHs was produced following changes to the assembly jig, glue curing temperature and fibre clamp. The overall quality of this second batch was vastly improved. The new fibre clamps and laser covers were well assembled, with one exception where the laser cover was detached from the laser driver ASIC onto which it was meant to be glued. A few issues were brought up with the second pre-production batch, notably the packaging and photodiode soldering. Several of the DOH boxes were squashed, having been forced into the shipping boxes. One photodiode was soldered onto a DOH PCB with insufficient solder.

Buffer ruptures were observed on a few of the first 10 DOHs produced as part of the second pre-production batch. The glue curing temperature was set to 60°C during the assembly of these 10 DOHs. Assembly of the remaining 27 DOHs was carried out at 40°C with no further buffer ruptures. However, it is expected that buffer ruptures will remain a problem and future lots will be inspected and the buffer ruptures repaired with flexible epoxy.

B. Geometrical Measurements

The nominal DOH size is 35 mm by 21.5 mm with a height of 5 mm. The tolerance is ±0.1 mm on all three dimensions and cannot be exceeded in the case of the width and height. The tolerance on the length is not critical. Measurements of the length, width and height of the DOH at several points, of the length of fibres as well as other layout features, such as the electrical NaiS connector, were carried out. The width specification was exceeded in some cases, reaching up to 22.3 mm, on DOHs with the CERN fibre clamp from the first pre-production batch. The PCBs had been cut very precisely, within the acceptable tolerances, but the laser covers and, in some cases the fibre clamps, were badly positioned. This problem was fixed in the second pre-production batch, with a fibre clamp redesign. The new fibre clamp is narrower and has a shelf onto which the laser cover can be accurately positioned.

Another critical distance is that from the NaiS electrical connector to the edges of the board. The maximum variation in length observed was 150 µm, which is considered to be acceptable.

V. FUNCTIONALITY TESTS

A test system was installed at Kapsch to check the basic functionality of DOHs before shipment to CERN, with a PASS/FAIL field on their packaging boxes indicating their status.

A custom test system was used at CERN to fully characterize the DOHs. The main feature of this system is that it allows for the testing of the transmitter path independently of the receiver path so that maximum information on eventual failures can be recorded and the cause of such failures identified.

All DOHs that passed the functionality tests at Kapsch also passed those at CERN, a total of 75 out of 77 DOHs. The two failures are discussed in section B.

A. The transmitter path: LLD and lasers

The laser output measurement is affected by the performance of the lasers and that of the laser-driver ASIC (LLD). The default laser output optical modulation amplitude (OMA) and average launch power (ALP) are shown for the following LLD voltage inputs: ±300 mV on 100 Ω, the optimum for specified LLD linearity, and ±250 mV on 100 Ω, the minimum input for the DOH specification (Fig. 4). The data are within specifications.

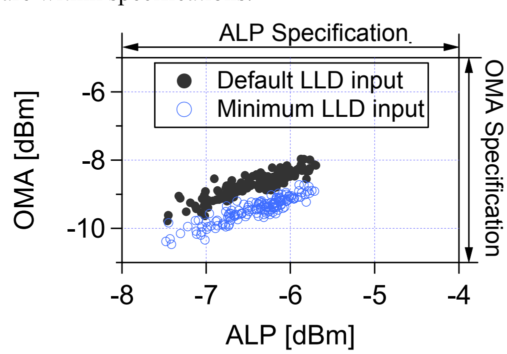

Figure 4: Default laser output OMA and ALP

B. The receiver path: RX40 and photodiodes

Of the 77 pre-production DOHs, 2 DOHs from the first pre-production batch had faulty Data receiver (Rx) channels. This was most likely due to a loss of signal in the photodiode, where there was some evidence that the fibre in the ferrule had been broken on two of the PD1 parts. The problem had already been detected at Kapsch and was confirmed at CERN.

The receiver channel sensitivity is a measure of the smallest signal it can detect. Sensitivity data for the remaining 75 DOHs (150 channels) show that most of these are within the -18 dBm specification (Fig. 5), with an average of -20.7 dBm. One channel was marginally above this limit. The minimum specified value for the receiver channel saturation is -3 dBm, which was met by all channels tested.

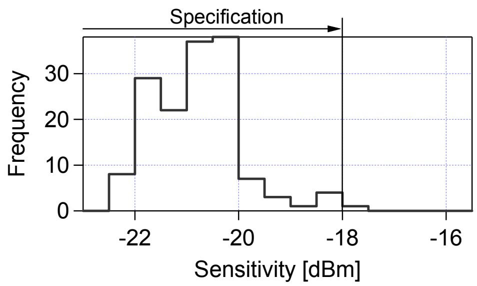

Figure 5: Receiver path sensitivity

The RX40 LVDS electrical output was found to be well above the minimum required output of ±250 mV.

The test procedure also checks the reset output of the RX40 chip, which is low whenever the data channel is held low for 250 ns (10 clock cycles at 40 MHz) or more. All functional DOHs passed this test.

C. Power Consumption and Supply Variation

The LLD features bias and gain registers that allow for the fine tuning of laser dc and modulation output characteristics. The power consumption was measured to be on average 265 mW for the default LLD bias settings, 76 mW for the minimum LLD bias settings (the lasers are effectively off) and 465 mW for the maximum LLD bias settings (Fig. 6). All DOHs were also tested at the minimum (2.25 V) and maximum (2.7 V) power supply voltages. No loss of functionality was observed at these extremes.

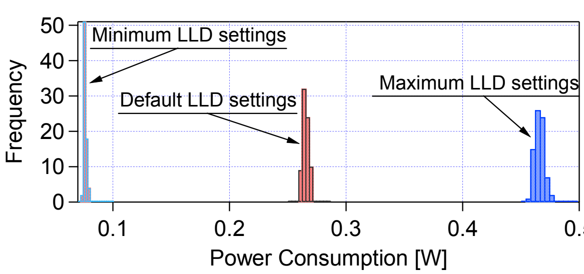

Figure 6: Power consumption measurements

D. Jitter

The jitter measurement consisted of feeding the DOH LLD input with a clock signal, coupling the laser output to the photodiode input, and sampling the RX40 differential output on a scope. The specification for DOH jitter is 250 ps rms. The highest observed DOH jitter was 53 ps rms.

VI. ENVIRONMENTAL TESTS

This section groups all the tests carried out to assess the reliability of the DOH in terms of environmental and handling robustness.

A. Thermal cycling

Six DOHs from the first pre-production batch were placed in an oven and put through 25 thermal cycles, whose structure consisted of a high temperature set-point of 40°C and a low temperature set-point of –20°C, with a ramp time between the two temperatures of 1 hour and a dwell time of 1.5 hours. The DOHs were powered throughout the test and the laser output characteristics were monitored periodically. Aside from the expected change of laser output characteristics with temperature, no damage or change in functionality was observed.

Thermal cycles were repeated for the second pre-production batch to check if the change in gluing procedure at Kapsch was acceptable. Twenty DOHs were put through thermal cycling tests unpowered and were fully functional after the test. One of the 80 fibres suffered a buffer rupture after the thermal cycling test. It is uncertain whether this buffer rupture was present but undetected before the thermal cycling or whether it occurred during the thermal cycling.

B. Magnetic field test

The magnetic field test was conducted on two DOHs. With three different orientations of the DOHs, no change in behaviour was observed at the maximum available field of 2.4 T.

C. Irradiation tests

Six DOHs were irradiated at room temperature with cobalt-60 gamma rays to 100 kGy in May 2004, and then with ~20 MeV neutrons between 6.3 and 9.1×10^{14} n/cm^2 in June 2004. During the neutron irradiation the DOHs were biased and measured in situ. The DOHs remained functional and the only measurable effects were those due to radiation damage in the lasers and photodiodes.

Although there is a noticeable degradation in the sensitivity of photodiodes after neutron irradiation, all 12 receiver channels operated above the -18 dBm (16 µW) specification (Table 4).

Table 4: Photodiode irradiation data

	Clock sensitivity	Data sensitivity
Prerad avg.	8.7 µW	9.1 µW
Gamma avg.	9.1 µW	9.2 µW
Neutron avg.	11.2 µW	11.9 µW
Difference (Prerad - gamma)	–5 %	–1 %
Difference (Prerad - neutron)	–29 %	–32 %

The radiation damage to the lasers after neutron irradiation is clearly apparent in Fig. 7. There is a spread of threshold values mainly because the DOHs were exposed to different fluences of neutrons. The measurements at higher LLD settings were taken with coarser steps, therefore the characteristics above the laser threshold are not smooth. The observed laser threshold shift is similar to that seen in previous studies where discrete lasers were irradiated with neutrons (20–25 mA for ~$5x10^{14}$ n or LLD shift of 44–56) [7].

The DOHs in the final system will suffer less damage than the DOHs tested here, and over the operational lifetime there should be more annealing of the damage. The estimated worst-case laser threshold shift is in the region of 6 mA [7] over the lifetime of the CMS experiment, corresponding to an I2C bias setting shift of 13. In other words, the threshold could shift from its pre-rad value of 11 to a value of 24, which is well below the default bias setting of 48.

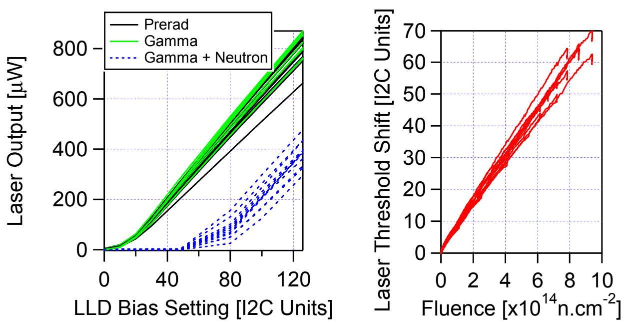

Figure 7: Laser output characteristics before and after gamma and neutron irradiation (left). Laser threshold shift as a function of neutron fluence (right).

D. Shock and vibration tests

The shock and vibration tests were carried out at Kapsch according to the IEC 60068-2 standard. Six DOHs were mounted on a cubic support structure, allowing stress to be applied along three perpendicular axes, on two DOHs per axis. Three shocks were applied to the support structure, using an in-house shock-testing station. The shocks were applied by decelerating at 200 ms^{-2} from a velocity of 11 ms^{-1}. The same support structure and the same six DOH samples used for the shock test were then used during the vibration test, conducted with the following settings: 12 minutes per sweep, 10 sweeps, 10 Hz – 58 Hz range, 0.35 mm constant amplitude and 58 Hz – 500 Hz, 50 ms^{-2}. All six DOHs were fully functional following the shock and vibration tests.

E. Fibre pull tests

Two types of pull test were conducted: “non-destructive” and “destructive” pull tests. In the case of the non-destructive pull test, a 700 g mass (corresponding to the original 7 N specification for the DOH optical fibres) was attached to the connector end of a fibre and the DOH PCB was lifted slowly until the fibre experienced the full 7 N force. Out of a total of 36 fibres tested, three fibres attached to lasers failed.

The destructive pull test uses a precise traction machine with a load cell that measures the force applied to the fibre. This test returns the value of the force required to destroy the fibre under test. A total of 32 fibres were tested, corresponding to eight DOHs. Two fibres, both coupled to lasers, were found to be below the 7 N specification with pull strengths of 6.7 N and 5.5 N.

Lasers and photodiodes undergo their own independent qualification and acceptance tests with pull-test specifications of 3 N and 7 N, respectively. The pull strength of fibres for parts mounted on DOHs was therefore considerably higher than the specification for lasers. The DOH pull-test specification has since been relaxed to 5 N.

VII. CONCLUSION

An extensive series of tests has been carried out to evaluate the reliability and robustness of the DOH following a well-defined set of procedures at the pre-production stage of the project. Although the functionality of the first batch of DOHs was found to be well within specifications, the overall assembly quality was unsatisfactory, with various defects on many DOHs. Due to these assembly defects, the first batch failed the qualification tests, prompting the launch of a second pre-production batch. The quality of the second pre-production batch was much improved over that of the first batch. The DOH has therefore been qualified and Kapsch has since begun final production.

VIII. ACKNOWLEDGEMENTS

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