Active Component Qualification for the CMS Tracker Readout Optical Links

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Abstract

We report on the completion of pre-production qualification of the laser transmitters and receiver modules for use in the readout system of the CMS Tracker. Detailed measurements of the opto-electronic and mechanical properties of the active components have confirmed that their performance fully meets the specifications of the optical link. Production can therefore begin and batch-level monitoring throughout production will ensure the performance of all installed components.

I. INTRODUCTION

The Compact Muon Solenoid (CMS) Experiment [1] will be installed at the CERN Large Hadron Collider (LHC) in 2007. The readout system for the CMS Tracker consists of 10 million individual detector channels [2] that are time-multiplexed onto 40000 uni-directional analogue optical links for transmission between the detector and the 65m distant counting room. The system must to be capable of pulse amplitude modulation at 40MS/s, with 8-bit resolution and 1% linearity. The link is chosen to be optical because of its immunity to electromagnetic interference, potential for low power and low mass, and provision of galvanic isolation between on- and off-detector electronics [3]. It operates single-mode at 1310nm wavelength.

An overview of the CMS Tracker Analogue Link is shown in Figure 1.

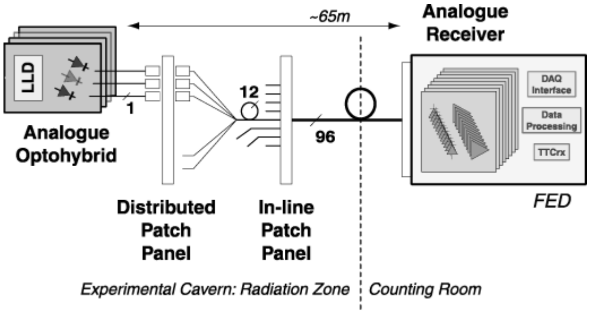

Figure 1: Overview of the CMS Tracker Analogue Link.

The custom-designed laser driver ASIC (LLD) [4] directly modulates the edge-emitting laser diode drive current to achieve light amplitude modulation which carries the information from the detector channels. Single fibres from the pigtailed lasers are connected at the periphery of the Tracker via small form-factor MU-type single-way connectors to a fan-in, which merges single fibres into a 12-fibre ribbon. There is a second break-point within the CMS Detector where the transition to a rugged multi-ribbon cable (8x 12-fibre ribbons/cable) is made via 12-channel MFS-type array connectors. In the counting room each ribbon connects directly to a 12-channel analogue optical receiver (ARx) module on the Front End Driver (FED).

The on-detector elements (i.e. lasers) will be distributed throughout the detector volume in close proximity to the silicon detector elements. In order to comply with the small available volume and harsh environment (-10°C operational temperature, 4T magnetic field, $\sim 3.4\mathrm{x}10^{14}/\mathrm{cm}^2$ fluence and ~150kGy dose expected lifetime radiation exposure [2]), strict requirements are placed on minimal package size, mass, power dissipation, immunity to magnetic field and radiation hardness.

It has been possible to meet the requirements with the extensive use of commercially available components with a minimum of customization. Commercially available laser packages are too bulky for use inside the detector volume, so a semi-custom package has been designed by an industrial partner for the chosen commercially off-the-shelf (COTS) edge-emitting laser die. The analogue off-detector receiver (ARx) is a modification of a commercial 12-channel digital module where the amplifier ASIC has been exchanged for a custom-designed analogue variant.

The production of the various elements that make up the optical links is the responsibility of several different industrial partners. As an example: for the pigtailed laser assembly the single fibre is produced by Ericsson (SE); the fibre is then cut by Sumitomo (JP) in pieces which are terminated at each end with MU connectors to build MU-MU jumpers; the jumpers are then shipped to ST (IT) who uses each jumper to create two pigtails for the lasers; finally Kapsch (AT) and G&A (IT) will mount the lasers on optohybrids. At the back end of the link, the amplifier ASIC designed by Helix (CH) is mounted in the 12-channel analogue receiver module by NGK (JP) before the module is mounted of the FEDs by RAL (UK).

CERN manages the interaction between the manufacturers and the flow of the parts. A bar code is assigned to each device produced in order to uniquely identify it. This allows complete traceability of the component history (for example, for each laser, it is known which fibre preform was used and which jumper).

By choosing COTS components, it is possible to benefit from the routine quality testing carried out by the manufacturers. Even so, CERN verifies the quality of the components in two phases (see Figure 2). Before mass production starts, a detailed Pre-Production Qualification is carried out, to test the performance of the first components produced, and compare it with the specifications [5]. In parallel, an Advanced Validation Test verifies that the products that will be used at the front-end are sufficiently radiation hard. Once Pre-Production and AVT tests are passed [6], the production process is qualified, and full production can start. After this point the stability of the process is checked through testing a small percentage of every produced batch (~5%). This phase is called Lot Acceptance and the tests are a subset of the Pre-Production tests. Its outcome is the acceptance or refusal of the inspected batch. Further information regarding the optical the Qualification Assurance process is available [7].

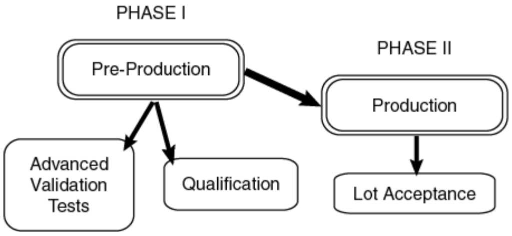

Figure 2: Production phases.

This paper describes the Pre-Production Qualification of the active components of the analogue optical link (lasers and receivers).

II. LASERS

The pre-production qualification of the lasers for the CMS Tracker Optical Link has been carried out over four months at the beginning of 2003 on 100 devices produced by ST Microelectronics.

The flow of the tests to be carried out on the batch is shown in Figure 3. The Lot Acceptance tests are grouped at the start of the Qualification (steps numbered 1-3). They consist of visual inspection, static and dynamic measurements. All the other measurements are performed only during pre-production qualification.

The visual inspection is the first step in every qualification or acceptance. It measures geometrical dimensions and checks for macroscopic defects visible to the naked eye. For the lasers the pigtail length is checked along with the package dimensions. Different pigtail lengths will be produced as there are different distances inside the Tracker between the analogue optohybrid, and the distributed patch panel (see Figure 1). For the qualification, the specified length for the pigtail was 1m, with a tolerance of –0mm/+20mm. 21% of the devices were found to be too long and 2% too short. This non-compliance was reported to the producer, who promptly solved it by cutting the pigtails with a more exact tolerance as verified on subsequent samples.

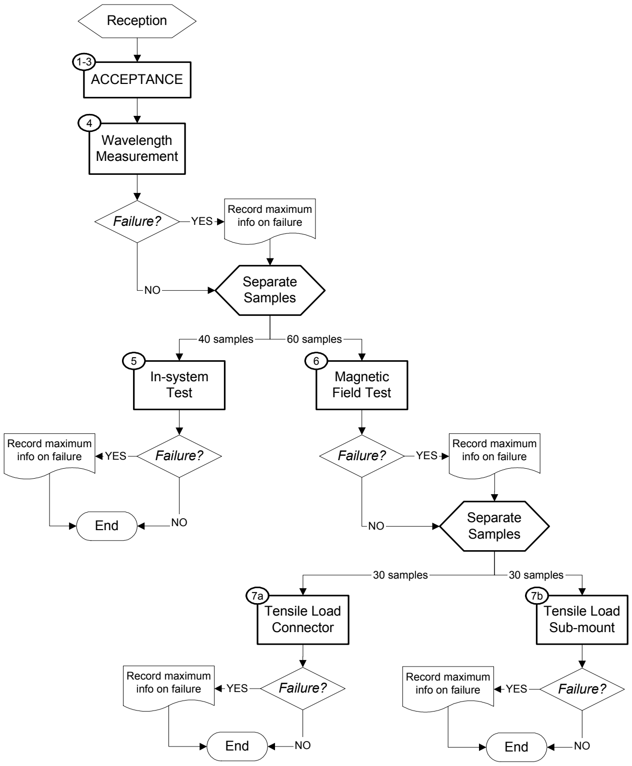

Figure 3: Test flow of the Pre-Production Qualification for the ST laser diodes.

The static measurement records the emitted optical power and the forward voltage while a laser driver varies the current applied to the laser. From the static measurement the threshold current, the efficiency, the maximum forward voltage and the series resistance of the laser are extracted, and checked versus the specification. Efficiency is defined as slope of the line fit to the power versus current characteristic, while the threshold is defined as the intercept of the same line with the x-axis. The threshold is specified to be lower than 10mA, and all the devices meet comfortably the specifications, as can be seen in Figure 4, where the typical value is 5mA.

Concerning the efficiency the limit values are 0.032W/A and 0.048W/A, shown in Figure 4 by the dotted lines. The values are in this case much more spread, filling all of the allowed range. Two devices were also found to be slightly out of specification. The producer tests all the delivered devices, guaranteeing they are in specification, and the fact that the CERN measurement leads to values that are not might be due to a difference in the system power calibration or in the temperature at the time of the measurement. This led to an agreement with the manufacturer: they will use tighter boundaries to choose which devices to send to CERN, so that small differences in the measurement set up do not make the devices go out of specification.

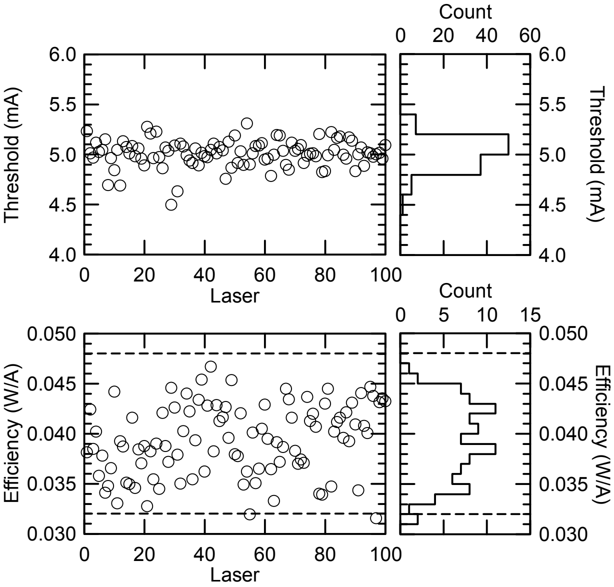

Figure 4: Calculated efficiency and threshold for 100 measured lasers.

The acceptance also includes a dynamic measurement, which checks that the laser is fast enough to comply with the system specification. The intrinsic bandwidth of the laser die is measured, and all the devices were found to be fast enough to comply with the 0.5ns specified rise time.

The wavelength spectrum was measured, making sure that the emitted light is in the range 1285nm to 1335nm. The values found were always very close to 1320nm whereas the typical specification is 1310nm. This difference may be caused by the dependence of the spectrum on temperature, but does not adversely affect the system performance in any way. The results are shown in Figure 5.

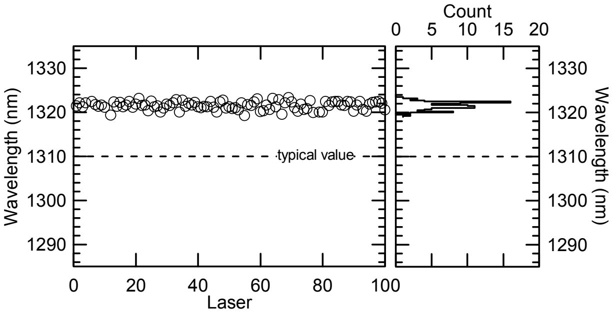

Figure 5: Wavelength results for all 100 pre-production lasers.

The in-system test of the pre-production qualification was carried out separately once lasers had been successfully mounted on pre-production analogue optohybrids and is therefore not described here. The successful operation of lasers mounted on optohybrids has since been shown [8] and the in-system test is deemed to have been passed.

The front-end of the link will be subject to a 4T magnetic field typical of the CMS environment and because of this, before the production starts and therefore in this qualification, a simple magnetic test was included in order to verify that the materials of which the devices are made were not magnetic. 10 devices were tested, and as they showed no movement if exposed to a 2.5T field, the test was passed.

The last test to be performed was the pull test which was carried out last as it destroys the sample under test. This test verifies the resistance of the joint between the fibre and the laser die. The other joint, the one between fibre and connector, had already been checked and qualified previously in the qualification of the MU-MU jumpers produced by Sumitomo. The pull test consists of stressing the joint until it breaks by pulling on the fibre and on the laser die on a pull-test machine. Out of the 57 devices tested, 14 broke before reaching the specified value of 3N. The process was thus considered unreliable and the producer was asked to change it slightly by glueing the glass of the fibre and not only the coating as previously. The two histograms shown in Figure 6 show the improvement observed after this process change. The newer tests show an improved average resistance and no failures which allows the full qualification of the lasers.

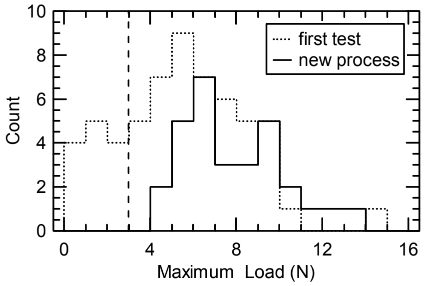

Figure 6: Pull test results for 57 pre-qualification devices (dashed line) and 30 qualified devices (solid line).

III. RECEIVER MODULES

The 12-channel receiver module consists of the module itself and the amplifier, so both components have to be qualified. Both pre-production qualifications were carried out during Q4 2002 and Q1 2003.

The first device to be qualified was the module which was qualified with a non-final version of the amplifier mounted inside it. The amplifier was qualified a few months later, mounted inside the final, already qualified, module.

The measurements carried out on the amplifier are a subset of those carried out on the module as, for example, they cannot include the mechanical specifications of the module. Although both amplifier and complete module have met all other specifications, we will describe only the following selection of tests in this paper:

- Visual Inspection (m)
- Return Loss (m)
- Static Measurement (a)
- Dynamic Measurement (a)
- Skew and Jitter (m)

in which the note indicates if the results relate to the module (m) or amplifier (a).

The visual inspection measures the dimensions of the outer package of the module and checks for macroscopic defects. All dimensions were found to meet the specifications, but small stains that were found on the optical connector were reported to the manufacturer who remedied the problem for later batches.

The return loss measurement checks that the optical connector does not reflect back too much of the incoming optical power, as such reflections would increase the noise in the system. The measurement is performed ten times for each module and an average of the return loss on the 10 re-mate cycles is taken. The average is specified to be better than 40dB for all channels of the module and all modules passed the test. Only the average value is taken into account as some dirt on the connector might fail a single measurement, while a repeatedly bad measurement would indicate a problem in the connector itself. For the same reason the connector is cleaned before every measurement.

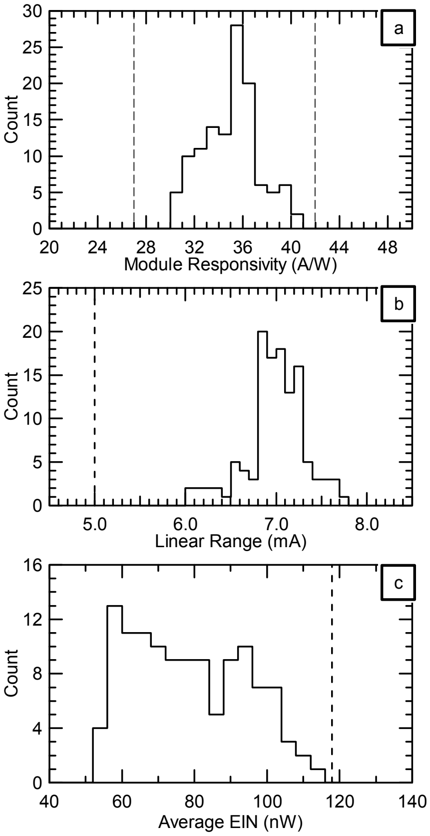

Figure 7: Figures of merit calculated for 10 modules, 120 channels in total.

The static measurement checks the linearity and noise properties of the module. In this test the module is fed with a varying optical input to simulate the operation in the final system, and then the transfer characteristic of the module as well as the noise performance of the test system and module is measured [9]. The input excitation comes from a laser with wavelength ~1310nm and covers the nominal optical input range of the module. Data is then extracted, leading to 5 figures of merit which are compared to the specifications. The module responsivity is measured from the gain of the transfer characteristic and is specified to be between 27 and 42A/W. The histogram in Figure 7 (a) shows the spread of the responsivity. The specification limits are represented by the dotted lines. The range in which the device has a linear behaviour is shown in Figure 7 (b), and must be greater than the link operational range. The noise, averaged over the operating range, should be compatible with the readout system resolution of 8bits over the operating range, which corresponds to 118nW Equivalent Input Noise (EIN) at the receiver (see histogram c in Figure 7). All channels of all modules met the specifications.

The dynamic measurement evaluates the speed of the module and verifies the matching of amplifier to photodiode array. The matching capacitance of the amplifier is tunable. It can be varied among four different values (800fF, 1000fF, 1200fF and 1400fF) using two control inputs. Through the dynamic test an indication of which control setting leads to the best-matching capacitance values can also be given. To perform the test, the receiver is fed with an optical square-wave input of period 200ns and 50% duty cycle. The output is sampled with a digital storage oscilloscope and all output signals for 12 channels of 10 modules are plotted in Figure 8, where different colours indicate the use of different matching capacitance values. The output is then used to calculate the 1% settling time and the 10%-90% rise time. In Figure 9 the calculated settling and rise times are plotted versus matching capacitance value. Higher values for the matching capacitance were found to give shorter rise times, but with an overshoot that effectively increases the settling time. A minimum value for the settling time of each channel of each module is found at a specific matching capacitance – the one that best matches the capacitance of the particular photodiode. The choice can only be made at a module level however, meaning that all channels of the same module must be set with the same matching capacitance value. From the results shown in Figure 9 (a) the choice would be between 800fF or 1000fF, while other batches may be different. This difference may be due to a photodiode or amplifier capacitance spread. The choice of which control settings to operate will be made when the modules will be mounted on the FEDs, but the fact that different solutions are possible will certainly help in having optimal behaviour in the final system.

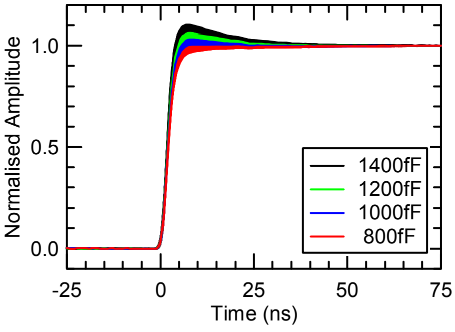

Figure 8: Receiver outputs for 12 channels of 10 modules and the four different capacitance values

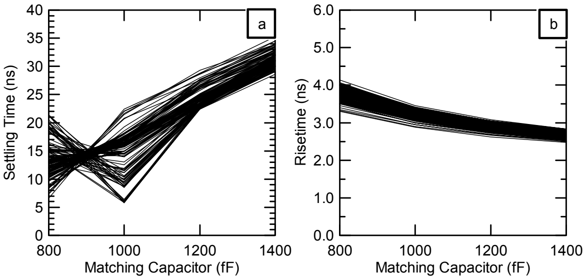

Figure 9: Calculated Settling Time and Rise Time for the data of Figure 8.

The dynamic measurement includes the measurement of cross talk between channels. The same optical pulse as for the rise and settling time is used. It is injected on one channel and the feed-through that this signal creates on other channels is measured. Cross talk is measured 20ns after the injection of the input pulse, and it is specified to be typically -60dB. The nearest neighbour channels are found to be slightly above the -60dB level (approx. -55dB), while all other measured channels are much lower (approx. -80dB). All modules are considered to have passed the test as the specification gives a *typical* value only.

Scanning the same optical pulse across the module channels and measuring the relative position of the rising edge of the pulse measured the module output skew. The relative delay among channels was measured to be lower than the specified 1.5ns when corrected by the supplementary delay added by the test board on which the module was temporarily mounted.

Jitter was measured by feeding the module channel with a 50% duty cycle square wave input and histogramming the module output. The root mean square value of the histogrammed values was measured to be less than the specified 0.5ns.

IV. CONCLUSIONS

The active components of the CMS Tracker analogue readout link and the production process flow have been described. In order for production to start, the components have been qualified by comparing the performance of the pre-production batches from their respective manufacturers against the relevant specifications drawn up by CERN.

A description of the qualification procedures that have been followed for the lasers and receivers has been presented. Some of the tests performed have been described in detail, and the results shown to fully meet the specifications. Minor functional problems have been solved through interaction with the manufacturer. In particular, the specified mechanical strength of the lasers has been achieved by the manufacturer having changed the production process. The specified performance for the components has thus been achieved and both active components are sufficiently low-noise, fast and linear for use in the analogue readout link of the CMS Tracker.

Following the component qualification, mass production has now started. Lot acceptance is on-going, with a reduced set of tests being carried out on a batch level to check the stability of the process. All but one of the passive components (the multi ribbon cable) have been qualified, and production of all optical link components will be complete by early 2005. This will allow the timely installation of the Tracker system inside the CMS detector, foreseen for 2006.

V. ACKNOWLEDGMENTS

The technical assistance of Christophe Sigaud in making the test set-ups used is gratefully acknowledged.

VI. REFERENCES

[1] The Compact Muon Solenoid Technical Proposal, CERN/LHCC 94-38, Dec 1994.

[2] CMS Tracker Project Technical Design Report, CERN/LHCC 98-6, Apr.1998, and Addendum, CERN/LHCC 2000-016, Feb. 2000.

[3] J. Troska, G. Cervelli, F. Faccio, K. Gill, R. Grabit, A. M. Sandvik, F. Vasey, and A. Zanet, "Optical Readout and Control Systems for the CMS Tracker", *IEEE Trans. Nucl. Sci.*, vol. 50, no. 4, pp. 1067-1072, Aug. 2003.

[4] G. Cervelli, A. Marchioro, P. Moreira, and F. Vasey, "A radiation tolerant laser driver array for optical transmission in the LHC experiments", *Proc. 7th Workshop on Electronics for LHC Experiments*, CERN/LHCC/2001-034, pp.155-159, Oct 2001.

[5] "Optical Links for CMS", Available: http://cern.ch/cms-opto

[6] K. Gill, R. Grabit, R. Macias, G. Papotti, J. Troska and F. Vasey, "Status of the Environmental Quality Assurance Programme for Lasers in Optical Links for Readout and Control Systems in CMS", *these Proceedings*

[7] K. Gill, R. Grabit, J. Troska, F. Vasey and A. Zanet, "Quality Assurance Programme for the Environmental Testing of CMS Tracker Optical Links", *Proc. 7th Workshop on Electronics for LHC Experiments*, CERN/LHCC/2001-034, pp.160-164, Oct. 2001.

[8] M. Friedl, "Analog Optohybrids for the Readout of the CMS Silicon Tracker", CMS CR 2003-026

[9] F. Jensen, C. S. Azevedo, L.Björkman, G. Cervelli, K. Gill, R. Grabit, F. Vasey "Evaluation and selection of analogue optical links for the CMS tracker - methodology and application", CMS note 1999/074