Final Results of the Industrial Production of CMS Tracker Analog Optohybrids

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Abstract

Approximately 15,000 analog optical transmitter modules with two or three channels each will be installed in the CMS experiment to read out the Silicon Strip Tracker. These Analog Optohybrids were produced in Austrian and Italian industries from mid-2003 to autumn 2005.

After assembly, each unit was thoroughly tested for electrical and optical properties and all results were stored in the CMS Tracker database, which allows a wide range of analyses. We will discuss statistical distributions of important parameters and their impact on the system.

Among minor issues, three significant problems occurred during the industrial production. Those will be described together with the corrective actions taken and the lessons learned.

I. INTRODUCTION

The CMS experiment at LHC will contain a Silicon Strip Tracker [1] covering a sensitive area of 206m^2 with 9.3 million strips. Groups of 128 strips are read out by the APV25 front-end chips and are consecutively multiplexed with the neighboring chips, resulting in roughly 36,000 data channels, each carrying 256 time-multiplexed analog strip signals at 40MS/s. Those data have to be transferred from the detector to the electronics hut over a distance of 60 to 100m, and optical transmission was chosen for this purpose.

II. OPTICAL READOUT SYSTEM

A. Overview

Figure 1 shows the principal components of the analog optical readout path [2]. The amplified detector signals are converted to optical by the Analog Optohybrid (AOH) [3,4] which consists of a Linear Laser Driver (LLD) ASIC [5] and two or three single pigtailed laser diodes. Groups of 12 and then 96 fibers are bundled in multi-ribbon cables which are guided to the 12-way pin diode arrays in the electronics hut for subsequent digitization and processing in the Front End Driver (FED) modules [6]. Similar, but bi-directional digital optical links [7] will be used for clock, trigger, reset and control distribution at much smaller quantities. This article is focused on the manufacturing of the front-end Analog Optohybrid, which is exposed to the harsh radiation environment in the CMS Tracker.

Both readout and control links use the same technology for signal generation and propagation. The laser transmitters are Fabry-Perot devices operating at 1310nm into single-mode, step-index optical fibers with 9/125/250/900µm of core/cladding/coating/buffer diameters, respectively.

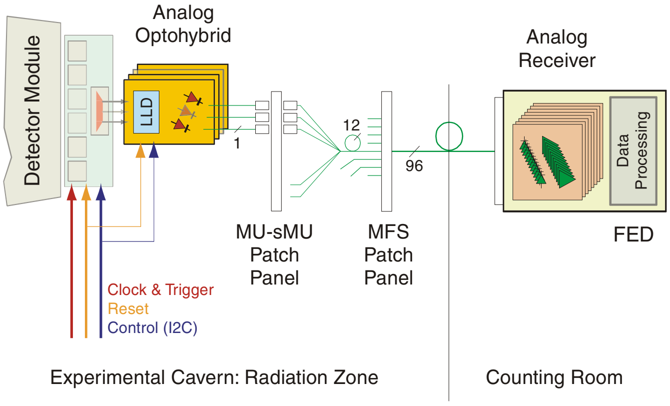


Figure 1: Block diagram of the Analog Optical Link of the CMS Silicon Tracker.

The light output is intensity-modulated following the input signal. Thus the optical signal bandwidth is the same as the electrical one (<100MHz), which is far below the capabilities of the optical system, but this principle was chosen in 1996 as a simple and robust design [8]. Significant progress has been made in optoelectronics since then, such that future optical links at S-LHC will be different to benefit from the advances.

B. Analog Optohybrid

Two or three laser diodes are contained in each Analog Optohybrid (Figure 2). Due to space constraints, a COTS optical connector could not be used, such that each laser had to be pigtailed with optical fiber terminated by an MU connector on the far end. Inside the laser package, the active semiconductor is glued and wire-bonded to the traces on the silicon submount, where bonding pads are also foreseen for the external electrical connection.

The laser diodes are driven by the Linear Laser Driver which essentially translates the differential input voltage into a suitable drive current. It has four selectable gains and an adjustable bias (offset) current to tune the light output range according to laser sample spread, potential losses at intermediate optical connectors and, most important, compensate the increasing laser threshold current with radiation dose.

The LLD is controlled by its I2C interface, where gains and bias currents can individually be set for each of the three channels. Figure 3 shows the block diagram of the AOH and the internal elements of the LLD in particular.

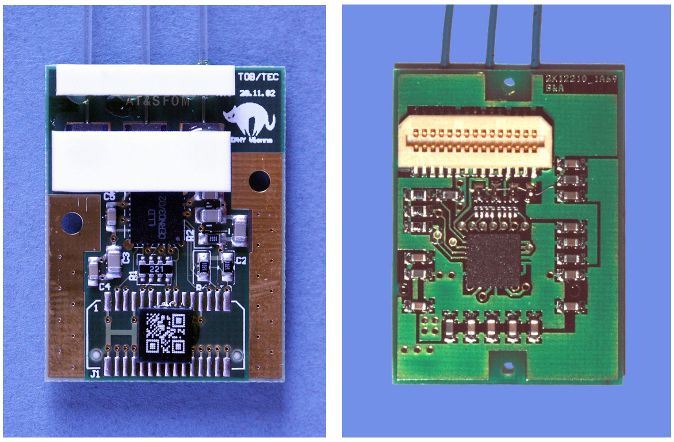


Figure 2: Analog Optohybrids (AOH) for the CMS Tracker: Outer Barrel (TOB, left) and Inner Barrel/Inner Disk (TIB/TID, right) versions. The PCB dimensions are 30x23mm^2 with the Linear Laser Driver (LLD) ASIC centered. The cover on top of the three pigtailed laser diodes protects the bond wires, and a similar piece is used for the fiber strain relief.

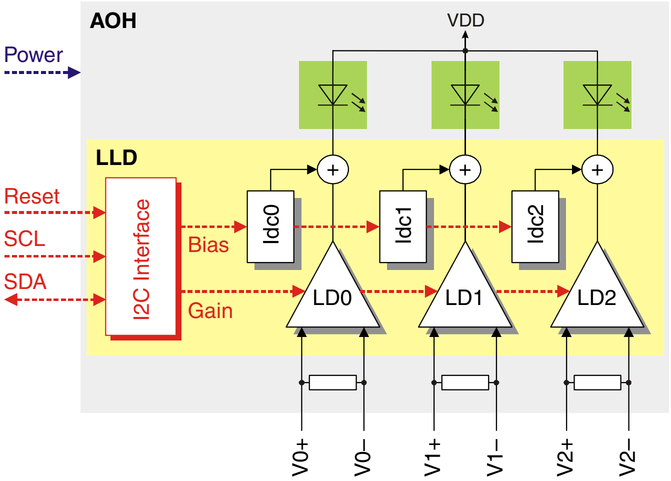


Figure 3: Block diagram of the Analog Optohybrid (AOH) and the Linear Laser Driver (LLD) ASIC contained within.

III. OPTOHYBRID MANUFACTURING

A. *Overview*

The AOH project was divided between HEPHY Vienna, responsible for approximately 13,500 devices for Outer Barrel (TOB) and End Cap (TEC) sections, and INFN Perugia, in charge of roughly 4,300 devices for Inner Barrel (TIB) and Inner Disk (TID) parts of the CMS Tracker, including spares in both cases. Due to specific geometrical requirements and constraints for each subgroup, different variants had to be built, differing in terms of connector type and location, two or three laser diodes, and the fiber pigtail length. Altogether, there were 28 such flavors with quantities between 53 and 1426 units each.

Significant time was spent for careful market surveys and prototyping with industrial candidates in order to find the most suitable company for the project. Finally, Kapsch Components [9] and G&A Engineering [10] won the tender procedure for manufacturing the Analog Optohybrids for Vienna and Perugia, respectively.

The following sections primarily describe the experience collected with the TOB/TEC production in Vienna, but similarly apply to the TIB/TID project and related optoelectronics devices like the CMS Digital Optohybrid or the CMS Gigabit Optohybrid, which are also manufactured at Kapsch Components.

B. *Assembly Process*

The assembly of SMD components onto a PCB as the first part of the AOH manufacturing is a standard industrial process. After that step, each board is electrically checked on an Automated Test Setup before lasers are assembled, since those are by far more expensive than the populated PCB.

Laser diodes are glued onto the PCB together with the strain relief and cured in the oven. Then, wire bonds are placed between laser pads and the PCB. The ceramic cover is glued on top of the lasers and a label dice is attached to the AOH, followed by another oven curing session. Finally, the device is thoroughly tested for electrical and optical performance on the Automated Test Setup.

This procedure does not only need non-standard machines (like a bonding station) and purpose-built jigs, but also requires a total of about ten minutes of manual work for each optohybrid. Moreover, the large number of different flavors creates some overhead in planning and exercising of the work in order to avoid mistakes. Unlike typical industrial products, the approximate split of material to labor costs is 40 to 60% for the Analog Optohybrid assembly. Due to the specific requirements, special components and several flavors are needed which do not allow cost-effective automation.

Another uneconomic issue is the long duration of the project which is essentially defined by the supply chain, taking about 1.5 years in Perugia and 2.3 years in Vienna. Moreover, users requested small quantities of each flavor in parallel according to their needs of installation. Thus, supply and production could not be streamlined to completely build one flavor after another.

C. *Problems*

Despite careful preparation and ISO 9000/14000 certification of the involved companies, three major and unexpected issues arose during the AOH production in Vienna, of which two were also relevant for Perugia.

The problem handling and solving gave some insight into the corporate culture of the company and the effort taken in the selection procedure proved worthwhile. In particular, the geographic proximity between HEPHY and Kapsch, both located in Vienna, allowed effortless interaction. Once more it turned out that the responsible contact persons at the company are a key point to successful collaboration.

1) *Laser Driver Package*

Shortly before series production of the Analog Optohybrid started, the original packaging company of the Linear Laser

Driver disappeared and another company had to be chosen for this task. The new package introduced grounded corner pads that were absent in the original package and caused shorts on the PCB (Figure 4). X-ray inspection was used to track down the problem during the pre-production phase.

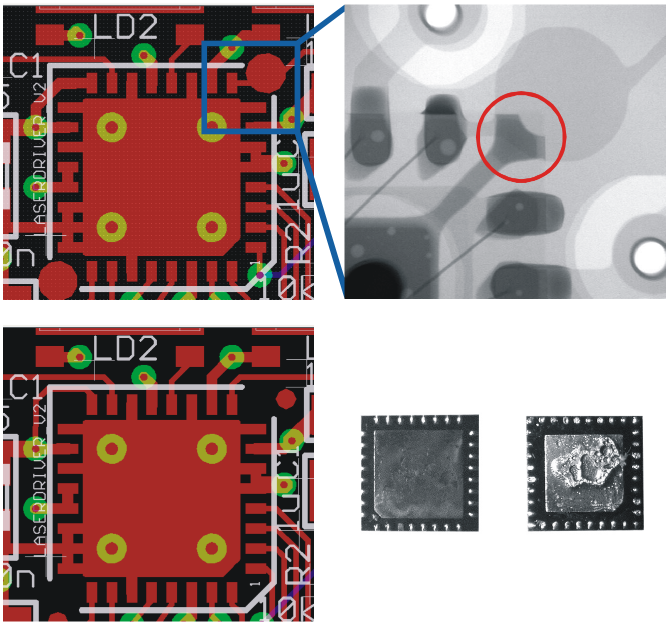


Figure 4: Top: Old PCB layout which led to shorts with the new Laser Driver package, as shown on the X-ray image to the right. Bottom left: Redesigned PCB with cleared corners. Bottom right: solder side of old (left) and new (right) Laser Driver ASIC package.

The only viable solution was a redesign of the PCB where the corners were cleared of any traces and vias. Luckily this problem happened in an early stage and less than 100 optohybrids were lost in total.

2) *Optical Fiber Defects*

Soon after the production started, it turned out that the acrylate buffered fiber pigtails suffered from mechanical problems ranging from scratches to buffer ruptures (Figure 5), where the outer coating is completely broken. Such defects do not affect the functionality, but carry a mechanical risk in the long term.

Several defects appeared at typical distances of the laser transmitter which could be attributed to jig edges used at the laser manufacturer for attaching the fiber to the laser pill. Those jigs were subsequently improved. Moreover, heating of the fiber – which is necessary to cure the glues that attach laser and fibers on the PCB – turned out to be another source of such mechanical defects. Systematic investigations were performed to correlate tiny defects initially present in the fiber with macroscopic ones appearing after thermal treatment.

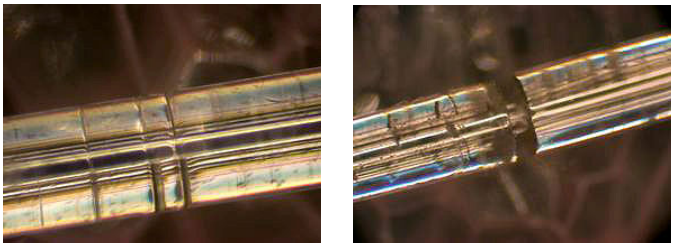


Figure 5: Optical fiber defects: cuts (left) and buffer rupture (right).

In order to generally reduce the number of buffer ruptures, the oven curing temperature, originally 70°C, was lowered to 44°C, where the creation rate of such defects was considerably lower, at the cost of significant impact on the production scheme since glue curing times were doubled.

Furthermore, it was decided to change the fiber to a Polyethylene-buffered type. Due to the long supply chain this change only took effect after about half the optohybrid production was done. No fiber defects were observed anymore with the new buffer.

3) *Capacitors*

After about 40% completion at Kapsch, it turned out that they had used their standard capacitor brand (AVX) instead of the specified one (Kemet), and AVX was not included in the irradiation qualification program. Thus, the production was halted and a comparative irradiation test was performed on both capacitor brands, consisting of 10MRad of gammas, followed by 5x10^{14} protons/cm^{2}. All capacitors were measured before, between and after the irradiation steps.

Luckily it turned out that Kemet and AVX are similarly radiation tolerant and all devices survived the irradiation with an average capacitance decrease of 17%, such that production could be resumed without change [11].

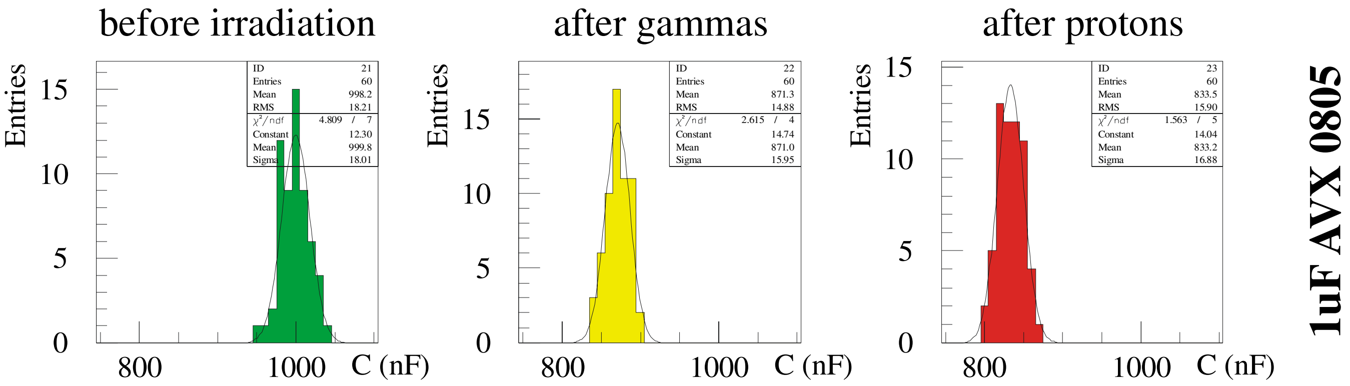


Figure 6: Capacitance decrease with gamma and proton irradiations for 60 devices of 1μF AVX. The spread remains unchanged.

IV. QUALITY ISSUES

A. Overview

The characteristics of the Analog Optohybrid are specified in [12]. The associated tests are split into qualification level, where all tests are performed on preproduction devices, and production level, where every object is checked for electrical and optical properties after manufacturing [13].

B. Qualification

The devices located inside the CMS Tracker volume have to endure harsh environmental conditions for the scheduled lifetime of ten years. In particular, those are an operating temperature of -10°C, a magnetic field of 4T and, worst of all, the radiation levels with an estimated $3x10^{14}$ hadrons/cm^2 and 15MRad gamma dose as the upper limit for the CMS Tracker.

All parts of the Analog Optohybrid and the assembled object were successfully tested for those conditions to ensure the principal functionality in the CMS environment. Details of these measurements and the results were reported in [14] and [15].

C. Production Tests

A sophisticated, but easily operated Automated Test Setup was built for industrial production and lot acceptance (sample) tests at the institutes in charge. The system provides an electrical test of the SMD-assembled optohybrid prior to laser assembly which takes less than one second.

Moreover, the Automated Test Setup offers a detailed electrical and optical check of the finished optohybrid, which needs about 39 seconds. Detailed measurements are performed and results compared to specified limits, such that the operator gets an overall pass or fail result. In case of a bad result, a compact error message and possible reasons are shown, while details are displayed for experts if requested.

The complete record of measurements is automatically sent to the institute in charge by email, where consistency checks are performed and the record is finally submitted to the central CMS Tracker database in Lyon. Moreover, a sound notification is sent to the desktop PC of the responsible person. The enormous advantage of such a system is that the production can be followed online as if the manufacturing was done in-house. Thus, instantaneous feedback or interaction is possible since the full information is immediately available. Moreover, web-accessible status reports are automatically created every night showing up-to-date tables and plots [16].

V. STATISTICS

A. Overview

Since the production of TOB and TEC type optohybrids is almost finished (90% completion as of 1 September 2005), we can derive statistical properties from the test results stored in the database. The most important figures will be shown here as a preview of the final qualification report to be published once the production is completed.

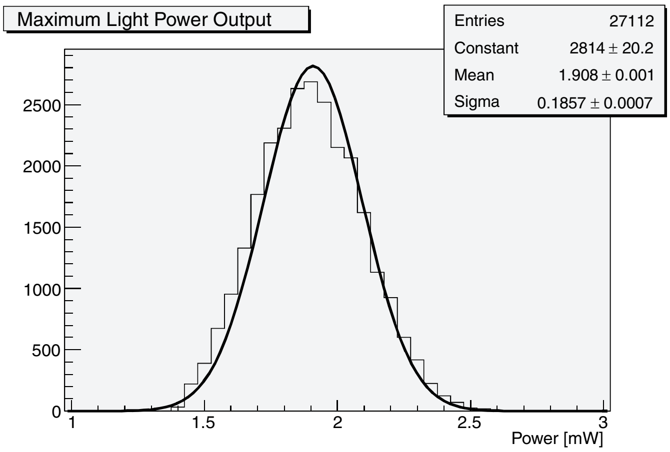
B. Throughput and Yield

The production started in mid-2003 and took 2.3 years to completion. Thus, the daily throughput was only 16 units in average, but peaking at 150 devices.

In the very beginning, the yield was as low as 50%, which is largely attributable to the Laser Driver Package problem, but also to a learning curve related to laser and fiber handling by the operators in the company. Already after 400 functional optohybrids, the overall yield exceeded the 80% mark and then the 90% level after another 400 devices. Later, it approximated 97% which was reached after about 50% completion and is stable since then.

C. Maximum Light Output

The maximum light output measurement indicates the proper functionality of the device and the optical path in particular. About 1.6% of devices contain one dark fiber channel and thus are marked as bad. Another 0.3% of channels show a non-zero light output below the specified minimum and thus are also considered faulty. Figure 7 shows the distribution of the maximum light power of good devices.



[mW]	min	typ	max
Specs	1.44	2.00	3.10
Measured	1.44	1.91	2.85

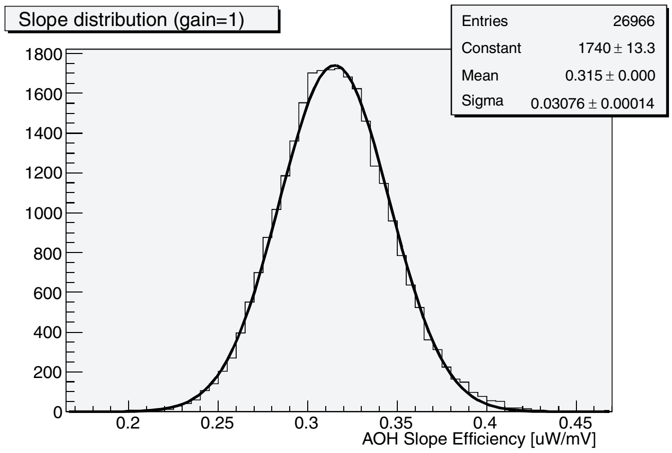
Figure 7: Maximum light power output distribution of about 27,000 channels on 11,500 TOB/TEC Analog Optohybrids. The minimum specification cuts off 0.3% of all channels at the low end of the Gaussian tail, which are considered faulty and thus not shown here.

D. Slope Efficiency

The slope efficiency shows if electrical signals are properly translated to optical. The specifications are observed by more than 99,9% of all devices. Figure 8 shows the distribution and numbers for gain=1, which is the typical operating condition for most devices.

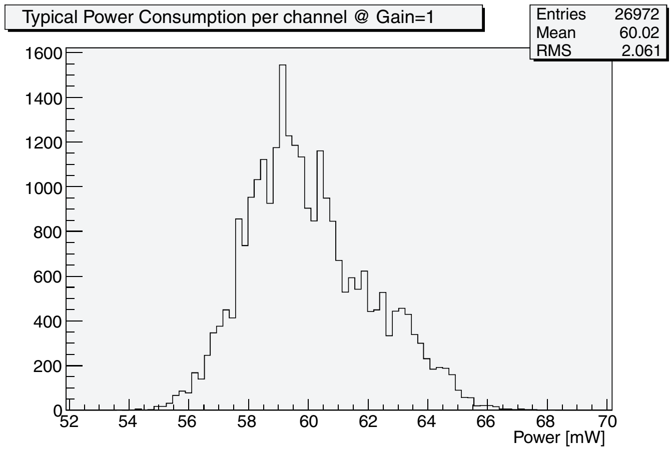
E. Power Consumption

The average power consumption of a single optical channel is about 60mW with standard settings at room temperature (Figure 9). All measurements are below the typical specification value. Furthermore, the average power per channel will be reduced to about 54mW at the operating temperature of -10°C due to the lower laser threshold current before irradiation. Thus, the complete Tracker Analog Optical links will consume about 2kW of electrical power.



[µW/mV]	min	typ	max
Specs	0.19	0.30	0.43
Measured	0.21	0.32	0.43

Figure 8: Slope efficiency distribution of about 27,000 channels on 11,500 TOB/TEC Analog Optohybrids. The upper limit is exceeded in five cases, which are considered faulty and thus not shown here.



[mW]	min	typ	max
Specs		72	
Measured	53.8	60.0	71.3

Figure 9: Power consumption distribution of about 27,000 channels on 11,500 TOB/TEC Analog Optohybrids.

VI. SUMMARY AND OUTLOOK

The production of about 17,800 Analog Optohybrids for the CMS Tracker will be successfully completed in October 2005 after 2.3 years of production. The unique requirements of the CMS environment required special devices and several variants which, together with the complicated supply and distribution chains, rendered this project uneconomical in many aspects from the industrial point of view.

Despite of ISO 9000 or 14000 certifications and careful preparation, we had to face three major problems which were all solved in good relation with the producing companies.

All assemblies were tested at the companies and results were automatically transmitted to the central CMS Tracker database. It turned out invaluable to follow the production quality by monitoring the test results online, allowing immediate feedback or corrective action, which is considerably easier and faster in case of geographical proximity. A close contact between the carefully selected manufacturer and the customer is clearly essential for the success of such a specialized project.

After completion of the project, the database will be used to extract statistical properties of the Analog Optohybrids. A preview is given here, revealing an overall yield of 97%, Gaussian distributed optical properties in good agreement with the specifications and a power consumption below expectations.

Stringent space constraints make it impossible to use the same objects for the CMS Pixel Detector, which requires about 1,500 analog optical links. Its Analog Optohybrid, containing six laser diodes, is currently being designed and approximately 300 devices will be produced in early 2006.

VII. REFERENCES

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