Experience with Large-Scale Industrial Production Considering the CMS Tracker Analog Optohybrids

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Abstract

Analog data will be read out of the Silicon Strip Tracker of the CMS experiment by the APV25 front-end chips. The data will be transferred to the electronics hut by approximately 15,000 optohybrids with two or three channels each. These units are being produced in Austrian and Italian industries, and more than 50% have been completed by September 2004.

We will describe the system, its components and what has been done to ensure its functionality within the CMS Tracker. Moreover, we will discuss issues arising from the transition of the manufacturing process from prototypes made in laboratory to large-scale production in industrial environment. We are convinced that many of these issues are not specific to the Analog Optohybrids, but are attributable to general differences between academic and industrial paradigms.

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] which consists of a Linear Laser Driver (LLD) ASIC [4] 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 [5]. Similar, but bi-directional digital optical links [6] 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 subjected to the harsh radiation environment in the CMS Tracker.

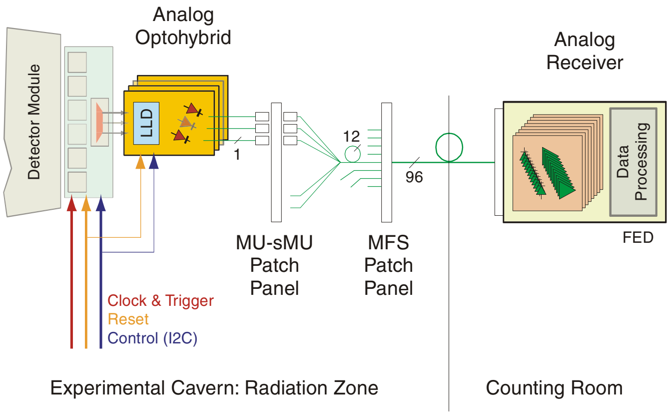

Figure 1: Block diagram of the Analog Optical Link of the CMS Silicon Tracker.

B. Optical Technology

Following long-distance telecom standards, the same technology was chosen for both analog and digital optical links [7].

Edge-emitting laser diodes were considered more matured and performing more linear than VCSELs. The wavelength of 850nm was discarded because that region is prone to radiation damage in the fiber and it is more dangerous to the human eye than the higher wavelength standards of 1310 and 1550nm, where components of the latter are more expensive. Finally, single-mode fiber with 9µm core diameter allows signal propagation at higher bandwidth and less distortion compared to multi-mode fibers with 50 or 62.5µm core, which are also more susceptible to modal noise.

Thus, the final choice were Fabry-Perot InGaAsP multi-quantum well lasers operating at 1310nm into single-mode, step-index optical fibers with 9/125/250/900µm of core/cladding/coating/buffer diameters, respectively. The light output is intensity-modulated following the input signal.

C. 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.

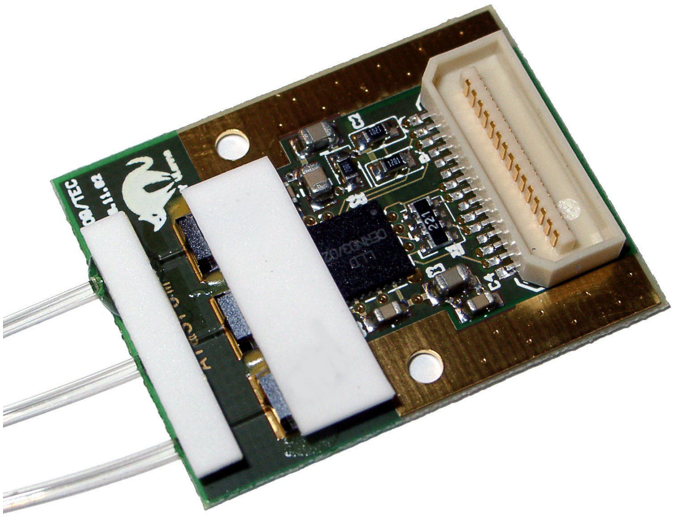

Figure 2: Analog Optohybrid (AOH) used in the CMS Tracker. The PCB dimensions are 30x23mm^2 with the Linear Laser Driver (LLD) ASIC centered. The ceramic cover on top of the three pigtailed laser diodes protects the bond wires, and a similar piece is used for the fiber strain relief.

The laser diodes deliver light output which linearly scales with the current above a certain level. Both slope and threshold current vary from sample to sample, are temperature dependent and affected by radiation damage. Thus, the Linear Laser Driver has four selectable gains and an adjustable bias (offset) current to allow operation in a defined light output power range (Figure 3) which is matched with the receiver side. Moreover, potential losses at intermediate optical connectors can also be compensated by adjusting gain and bias.

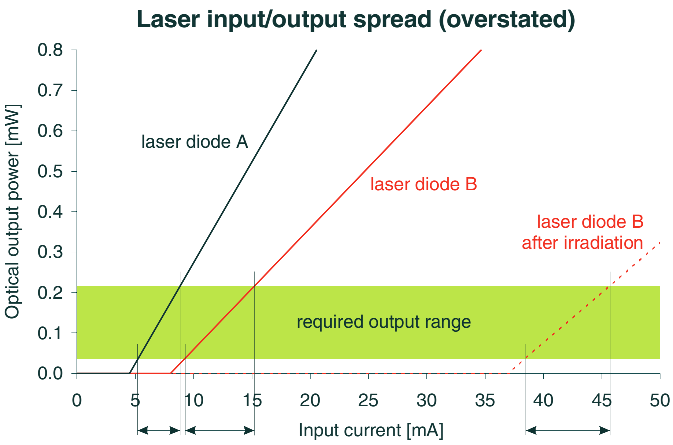

Figure 3: Exaggerated sample spread of the input/output characteristics of the laser diodes. The shaded area indicates the optimum light output power range, which can be reached by individual bias and gain settings in the Linear Laser Driver (LLD).

The LLD is controlled by its I2C interface, where gains and bias currents can individually set for each of the three channels. While it receives differential voltage signal inputs, the output stage delivers current signals suitable for the laser diodes. Figure 4 shows the block diagram of the AOH and the internal elements of the LLD in particular.

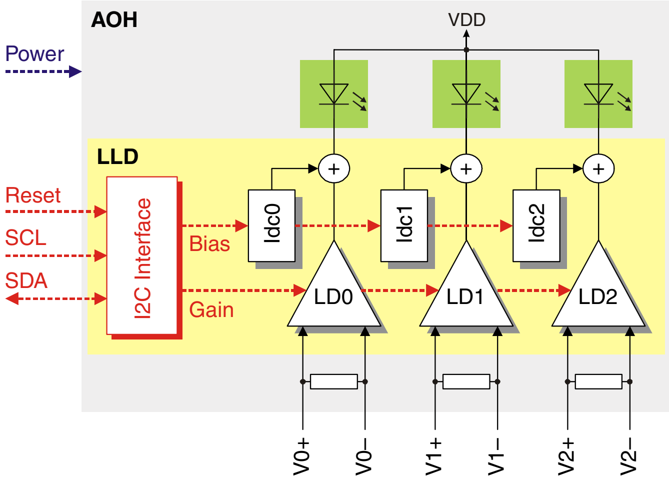

Figure 4: Block diagram of the Analog Optohybrid (AOH) and the Linear Laser Driver (LLD) ASIC contained within.

III. OPTOHYBRID MANUFACTURING

D. *Overview*

The AOH project was divided between HEPHY Vienna, responsible for approximately 13,000 devices for Outer Barrel (TOB) and End Cap (TEC) sections, and INFN Perugia, in charge of roughly 4,000 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, slightly different variants were developed. In the prototyping phase, the AOHs were iteratively optimized before mass production started.

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. Moreover, we are convinced that the symptoms shown and conclusions drawn here do not only apply to the optical links manufacturing, but – in a conceptual meaning – to the interaction between scientific and industrial worlds in general.

E. *Assembly Process*

The assembly of SMD components onto a PCB as the first part of the AOH manufacturing is a standard industrial process which is highly automated and has an enormous throughput. Even though the LLD package has small pin spacing and its solder pads on the bottom of the case which makes them invisible to optical inspection, 13,000 PCBs can easily be populated within a few hours with a yield in the order of 99%. Admittedly, that process requires some initial adjustments to the temperature profile of the solder reflow oven and possibly x-ray inspection of the results, but nevertheless those are again procedures well-known by industrial electronics manufacturers. The total cost of the SMD assembled optohybrid, including PCB and components, prior to laser mounting is about €8. Since this is much cheaper than the laser diodes, each board is electrically checked on an Automated Test Setup before lasers are assembled.

Now, the laborious manual work starts. Laser diodes are glued onto the PCB together with the strain relief and cured in the oven. Then, wire bonds are manually 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. The overall cost of the laser assembly per AOH (including non-recurring costs) is about €16, where the main fraction is manual work.

The most expensive component of the AOH is the laser diode at €65, which contains an estimated fraction of 50 to 60% of manual labor costs and thus is similarly labor intensive as the AOH assembly.

Overall, we can derive an approximate split of material to labor costs of 40 to 60%, whereas the typical industrial electronics production divides roughly 80 to 20%. The reason for this particularity is that because of the unique requirements, we have special components in quantities which are rather small at industrial scale, and thus a high degree of automation would not be cost-effective.

However, a large fraction of manual work is not the only uneconomic issue we have to face. Based on the space constraints mentioned earlier, various lengths of the laser pigtail fibers are needed to fit the objects into rod and petal structures. Moreover, slightly different AOHs were developed for the sub-detectors and optohybrids with two or three lasers are required to match the detector modules' strip count. This results in a total of 22 variants of the AOH device already for TOB and TEC alone, which implies some administrative effort and increased lot costs, since the AOH users typically request small numbers of each variant in parallel according to their need for the assembly of AOHs onto larger structures.

F. Company Selection

Contrary to standard industrial products, it is obviously difficult to find a company suitable for the manufacturing of a specialized device like the optohybrid with all the uneconomic factors mentioned earlier.

In the case of the AOH, the company needs to be equipped with a bonding station, which is more likely with big companies. On the other hand, it has to perform a large fraction of non-automated, manual work, which tends to be easier with small companies. Moreover, the manufacturing process (and the company itself) should be stable over the full duration of the project.

Thus a medium-sized company should be the best trade-off for these contradictive requirements and in fact the market survey demonstrated that neither big nor small companies could and would perform the AOH manufacturing.

Money certainly is an important issue, but it has shown that quality and the efforts taken by the company are more important with such specialized devices. In particular, the pigtailed laser diodes are fragile optoelectronics components which require some training for proper handling. Moreover, geographical proximity is invaluable for effortless interaction which is required more frequently than for standard products. Even if manufacturing might be cheaper in the Far East, the effort and cost of traveling might easily eat up this bonus.

The CMS TOB/TEC AOH production is entirely funded by Austria, and the request was made that this money is in turn spent in Austria, which is an option within the CERN purchasing rules. 18 local companies were contacted in the market survey, which led to four preliminary offers and subsequent prototyping with the lowest bidder. However, quality and effort were not satisfactory such that samples were ordered from another bidder, Kapsch Components [8], who turned out more suitable and was ultimately chosen despite of a slightly higher final bid.

Thanks to the good experience with the AOH, Kapsch was later invited to bid for the Digital Optohybrid (DOH) used in CMS Tracker and ECAL as well as for the Gigabit Optohybrid (GOH) of ECAL and eventually won both contracts. Thus the skills that Kapsch gained on the AOH turn out beneficial to the similar DOH and GOH projects which contain the same type of laser diodes.

G. Logistics

As shown in Figure 5, the flow of components is quite complicated and involves several European and Japanese companies. Thus it is prone to delays which propagate throughout the chain. Furthermore, the throughput is given by the slowest element, which is the pigtailed laser assembly in our case, defining the project duration of almost two years.

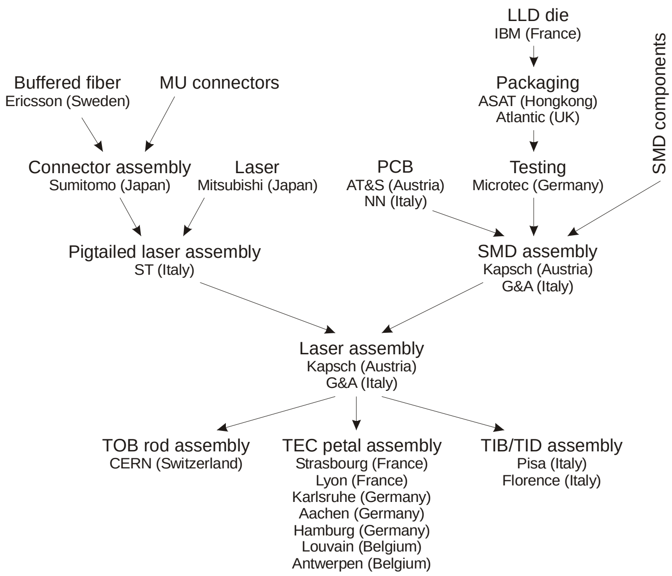

Figure 5: Flow of components around the SMD and laser assembly of the Analog Optohybrid (AOH) manufacturing.

The manufactured AOHs are distributed to several rod and petal assembly centers where they are mounted on larger structures together with detector modules, interconnect boards and other objects. Similarly, that assembly is very susceptible to delays since it relies on various input components and indeed delays occur, which in turn slow down the user feedback to the companies earlier in the chain.

IV. QUALITY ISSUES

H. Overview

The characteristics of the Analog Optohybrid are specified in [9]. 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 [10]. While the target of the qualification is to demonstrate that the device is generally fit for its application in CMS, the production testing is primarily meant to spot component or assembly faults.

I. 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 with occasional (about once a year) few-days periods at room temperature, a specification which is not uncommon from the viewpoint of industry, where many devices face worse conditions, e.g. in the car industry. The operating temperature range is usually specified for each component and it is quite easy to find parts which meet the CMS requirements.

In contrast, little information is found on the compatibility with a magnetic field of 4T which essentially implies that all ingredients must be non-magnetic. Moreover, semiconductor devices such as the laser diodes could suffer and thus must be tested in such an environment. The most non-standard requirement, however, is the radiation. Some information exists for space applications, but the radiation environment there is less aggressive than in an LHC experiment and thus is not very useful for our purpose. The only possibility to learn about the compatibility with the estimated $3x10^{14}$ hadrons/cm^2 and 15MRad gamma dose estimated as the upper limit for the CMS Tracker volume over ten years is to perform such irradiation tests. Even though it is impossible to exactly simulate the particle and energy mix that will occur in the experiment, results with different types of particles and fluences in excess of the expected ones give an indication of the potential damage of each particle category.

In fact, irradiation tests with protons, neutrons and gammas were performed on the component level including PCBs, SMD resistors and capacitors, the LLD, lasers and glues. While these experiments confirmed that PCB, LLD and lasers are suitable for the radiation environment, the tests were competitive among various brands and types of SMD components and glues. In general, most types turned out to be compatible with the CMS radiation levels, but different levels of degradations were found particularly with capacitors. Brands and types were specified according to the best results of the irradiation tests. Finally, prototype optohybrids, built with the specified parts, were irradiated and positively confirmed the component level tests.

Laser diodes and the APV25 front-end chip were tested in a magnetic field of up to 10T parallel to every axis [11]. It was found that the impact on the laser performance was negligible while the APV25 was not affected at all. Since the LLD is manufactured in the same 0.25μm CMOS technology, we can assume analogous behavior there.

Concerning the temperature, several production-grade optohybrids were subjected to thermal cycles and long-term operation in the cold. Moreover, the AOH performance was tested versus temperature in the range of -15 to +20°C.

The overall result of the qualification was positive. Details of the tests, including statistical distributions of the electrical and optical parameters, can be found in [12].

J. 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 board-level test of the SMD-assembled optohybrid prior to laser assembly which takes less than one second. This test is intended to prevent the assembly of expensive laser diodes on non-functional PCBs, and no data are recorded.

Moreover, the Automated Test Setup offers a detailed electrical and optical check of the finished optohybrid. The operator has to plug the optohybrid both electrically and optically, scan the serial numbers of optohybrid and laser pigtails and enter the pigtail length. Then, the software initially repeats the electrical board-level test and later scans most of the specified optical parameters, which takes about 39 seconds in total. Since the operator is idle during that time, dual-channel systems were provided to industries such that another optohybrid can be prepared or removed from the second nest while a test is in progress on the first one. Detailed results are given on a text log and in an optionally displayed graph window, but those are meant for experts rather than the average operator who gets an overall pass or fail result. In case of a bad result, a compact error message and possible reasons are shown. Finally, a label is printed and attached to the optohybrid box, indicating the serial number in both human-readable and barcode representations, technical data and the summarized result.

The complete record of measurements is stored on the local hard disk and at the same time is automatically sent by email to the institute in charge in binary and XML formats, where the latter is composed suitable for submission to the central CMS Tracker database in Lyon. Automatic scripts process the incoming data emails at the institutes, perform consistency checks and submit the verified XML files to the database. Moreover, a sound notification is sent to the desktop PC of the responsible person. This procedure is shown in Figure 6.

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 day showing current tables and plots [13].

Custom software which interacts with the Automated Test Setup is also used for shipping of final optohybrids and rejection of incoming laser diodes. The shipping software produces database-compliant transfer lists, which are also sent to the institute in charge by email, and ensures that only functional devices can be sent in a sorted way.

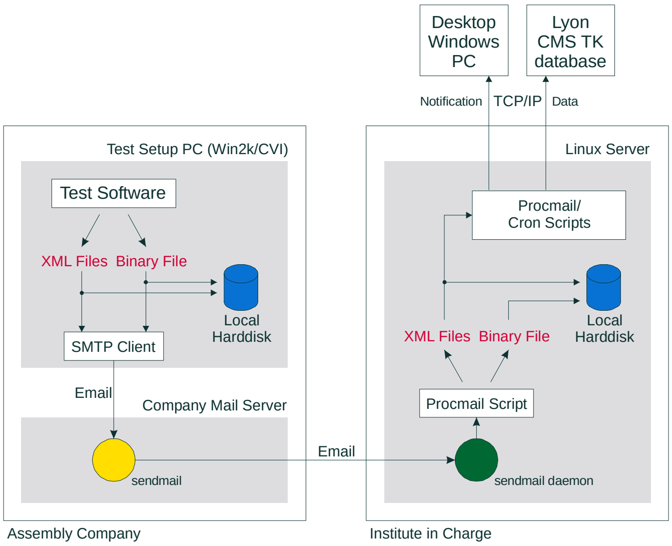

Figure 6: Data flow of the Analog Optohybrid (AOH) test results from the Automated Test Setup in industry (top left) through the company mail server (bottom left) to the institute in charge (right). Finally, data are submitted to the central database and a notification to a desktop PC is generated (top right).

K. Problem Handling

Initially, the procedure of laser assembly was slightly different from its final state and iterative improvements and optimizations characterized the transition from laboratory prototyping to industrial series production. Tiny adjustments with moderate effects on throughput or yield do not matter in the lab, but multiply by thousands in the series production and thus become relevant there.

At 56% of completion in September 2004, the overall yield of the AOH assembly at Kapsch is 96.5% at a throughput of up to 150 devices per day. This is the achievement of an initial learning phase where both yield and speed were much lower, attributable to both non-optimized procedures and imperfect handling by the operators.

During the steady production with the quality assurance methods described above, errors are quite rare. There have only been a few cases where code labels were scanned in wrong order or an incorrect pigtail length was selected, both human errors. Those cases, however, can be spotted and corrected by consistency checks during tests on a higher level, i.e. when AOHs are assembled onto rod and petal structures.

A more general issue emerged after about 40% of completion, when it was discovered that Kapsch had used capacitors of a brand different than specified. Since that manufacturer was not tested for radiation tolerance before, it was unclear whether the parts were suitable for use in the CMS Tracker. Kapsch admitted its mistake, the production was halted and those capacitors were checked for proton and gamma radiation damage in competition with the originally specified brand. Luckily it turned out that they were equally resistant to radiation such that production could be resumed. Otherwise, all capacitors on several thousands of existing boards would have had to be changed manually, a task which would not just have been troublesome and risky, but also a logistical nightmare since the objects were distributed to many locations and already partly assembled onto rod and petal structures.

V. Concluding Remarks

By the example of the Analog Optohybrids, it is obvious that industrial series production does not simply mean to continue laboratory prototyping on a different scale. Paradigms of scientific and industrial worlds are different in many ways, e.g. concerning quantities, number of variants, degree of automation, duration or specifications for the production of electronics devices. Many of the scientific requirements are inherent and thus cannot easily be “industrialized”. However, some consensus might be found by careful design trade-off, e.g. limiting the number of variants.

We found that problems appear where humans work despite of ISO 9000 or 14000 certifications and it is rather the corrective approach, or corporate culture, which matters. Similarly, the price does not necessarily tell something about the actual quality. Thus it is essential to gain some experience with the company and the people involved prior to signing a contract in cases of non-standard manufacturing.

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 manufacturer and customer is clearly essential for the success of such a specialized project.

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