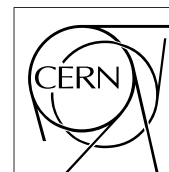


The Compact Muon Solenoid Experiment

# CMS Note

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## Experience in the development of the CMS Inner Tracker Analog Optohybrid Circuits: Project, Qualification, Volume Production, Quality Assurance and Final Performance

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### Abstract

The Tracker system of the Compact Muon Solenoid (CMS) Experiment, will employ approximately 40,000 analog fibre-optic data and control links. The optical readout system is responsible for converting and transmitting the electrical signals coming out from the front-end to the outside counting room. Concerning the inner part of the Tracker, about 3,600 Analog Optohybrid circuits are involved in this tasks. These circuits have been designed and successfully produced in Italy under the responsibility of INFN Perugia CMS group completing the volume production phase by February 2005.

Environmental features, reliability and performances of these circuits have been extensively tested and qualified. This paper reviews the most relevant steps of the manufacturing and quality assurance process: from prototypes to mass-production for the final CMS use.

# 1 Introduction

The Silicon Strip Tracker System of the Compact Muon Solenoid Experiment [1], presently under construction at CERN, consists of 9,300,000 silicon microstrips arranged in a multilayer cylindrical structure around the particles interaction point at the centre of the detector [2]. The structure is subdivided into an inner section, consisting of the Tracker Inner Barrel (TIB) and Tracker Inner Disks (TID), and an outer section composed of the Tracker Outer Barrel (TOB) and Tracker End Caps (TEC) covering in total a sensitive area of  $206\text{m}^2$ .

An analog optical readout system [3] has been developed for transmitting the data between the detector and the back-end electronics, situated into a counting room, over a distance of 65 to 100m. Data from the silicon microstrips are processed by the APV25 front-end ASIC [4] chips and subsequently time-multiplexed (256:1) for the transmission over the analog optical channels. Approximately 36,000 fibre-optic data channels are required to carry the information signals coming out from the front-end modules electronics. The analogue data transmission requires a system capable of pulse amplitude modulation at 40MS/s with 8-bit resolution and 1% nonlinearity over the  $\pm 300\text{mV}$  input operating range. For this purpose the Analog Optohybrid (AOH) circuit [5] has been conceived and developed.

## 2 Analog Optohybrid Description

### 2.1 Overview of optical link features

A scheme of the analog optical link for the CMS Tracker is reproduced in Figure 1.

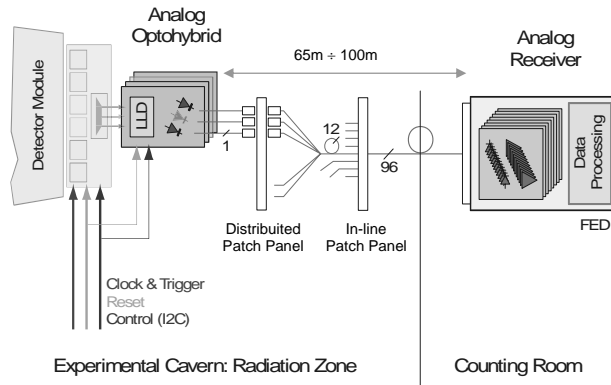


Figure 1. Analog optical readout chain of the CMS Silicon Strip Tracker.

The differential input voltage signals processed by the detector front-end electronics are converted in optical by the Analog Optohybrid circuit which essentially houses a Linear Laser Driver (LLD) ASIC programmable chip [6] and two or three single pigtailed laser diodes [7].

The optical fibres coming out from the AOH circuits are inserted in a first patch panel and fanned into a 12-channel ribbon. Groups of 8 ribbons are then bundled in multi-ribbons cables guided to the optical receiver in the counting room for subsequent digitization and processing in the Front End Driver (FED) modules [8].

The functionality of the whole analog readout chain is controlled by signals transmitted by similar, but bi-directional, digital optical links based, as far as possible, upon the same components [9].

## 2.2 TIB/TID AOH circuit characteristics

INFN Perugia CMS group has been responsible of the design, engineering and mass-production of roughly 4,300 Analog Optohybrid circuits (Table 1) to be employed in the 9,500 TIB and TID analog optical links. HEPHY Vienna is similarly responsible for approximately 13,000 devices for the TOB and TEC [10].

Table 1. INFN Perugia AOH production numbers. Spares include also a quota (140) used for tests on a TIB prototype.

INFN Perugia AOH production	Numbers
QA qualification (pre-production)	50
Assembly on TIB/TID	3540
Spares	700
<b>Total</b>	<b>4290</b>

The TIB/TID AOH, which is the subject of this paper, uses a 4-layer FR4 PCB with components mounted on both faces (Figure 2). To interface to different geometries of the silicon modules (to which each AOH is directly interconnected), the AOH has been developed with six different versions.

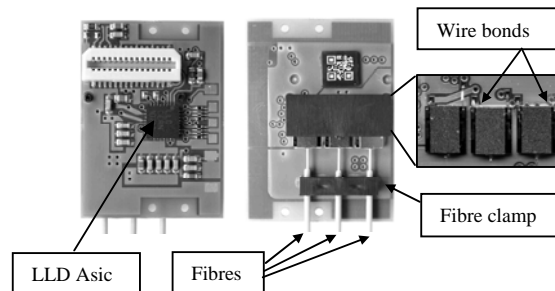


Figure 2. The TIB/TID AOH circuit (front and back). On the right a close up of the lasers, under the cover, connected with wire-bonds.

The Linear Laser Driver chip [6] (CMOS 0.25 $\mu$ m technology) operates the voltage-to-current conversion of the differential input signals and then, using unipolar current, directly modulates the edge-emitting laser diode. The LLD is controlled by the I<sup>2</sup>C interface which permits to set the gains and diodes bias values individually for each channel as shown in Figure 3. The laser driver ASIC, designed by the CERN Microelectronics group, has a programmable output which allows to change both slope and threshold current of the diodes in order to compensate the radiation damage, temperature variations as well as power losses at intermediate optical connectors.

Laser diodes produced are Fabry-Perot InGaAsP/InP multi-quantum well COTS (Commercial Off-The-Shelf) components, designed and produced by STMicroelectronics [11], operating at 1310nm into single-mode step-index optical fibres (with 9/125/250/900 $\mu$ m of core/cladding/coating/buffer diameters respectively) terminated by an MU connector. For these lasers, a specific package has been defined and extensively tested by both STM and CERN CMS Optoelectronics group.

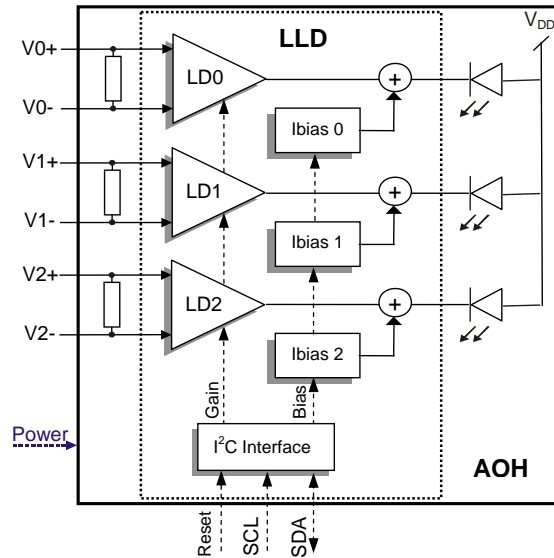


Figure 3. Block diagram of the Analog Optohybrid (AOH) and the Linear Laser Driver (LLD).

### 3 Circuit Manufacturing

The harsh operative conditions of the CMS environment (operating temperature at  $-10^{\circ}\text{C}$ , magnetic field of 4T, radiation dose up to 100kGy and  $3.4 \cdot 10^{14} / \text{cm}^2$  particle fluence in the nominal 10-years lifetime) impose strict requirements: not only electrical constraints such as power dissipation, immunity to magnetic field, radiation hardness and reliability but also mechanical ones such as minimal package size, low mass, robustness and easy-handling.

In order to satisfy to these requests, before to start with the mass production, the AOH underwent to an iterative process of optimization, along a period covering the project definition and the prototyping phases.

The large amount of optical links present in CMS imposed an effort in order to minimize the resources required for the development and production. The choice that has been made was to apply to the manufacturers for telecommunications applications using commercial off-the-shelf components or devices based closely on COTS where possible.

In the AOH case we have to consider that it will be practically inaccessible during most of ten-years of lifetime, so maintenance or replacing will not possible. Thus components placed on it must be guaranteed not only to be immune to magnetic field but, especially the optical ones, also capable to compensate the radiation effects and operate between a range of temperature down to  $-10^{\circ}\text{C}$ .

All components of the AOH have been extensively qualified to be radiation hardness and non-magnetic and, before the volume production, the whole circuit has been irradiated and qualified in operative conditions [12].

#### 3.1 AOH development

Before the volume production, a big effort has been done to optimize the circuit in order to attain the final version. We can distinguish two stages during which the AOH characteristics have been tailored to the system requests and specifications: the early prototypes and the later prototypes.

The first one has been essentially devoted to find out the best solution among various possibilities in terms of choice of components and assembly technologies. The earliest prototypes were realized for example on a ceramic thick film substrate of Alumina ( $\text{Al}_2\text{O}_3$ ) with components mounted on a single face (Figure 4). The LLD was an unpackaged die directly bonded on the substrate and the laser diodes which were present at that time, came in two different versions from different suppliers. Also the fibre and connectors (FC/PC) were quite different from the present choice.

Three different early prototypes were produced following R&D at CERN and INFN laboratories, in order to attain the right choice for sub-components as well as assembly technologies. Alumina substrate finally was rejected in favour of FR4 (vetronite), which is less expensive and in any case still acceptable from the thermal properties point of view. STMicroelectronics lasers have been also chosen, combined with acrylate-buffered fibres<sup>1</sup>, from Ericsson, coupled with a MU-type connector from Sumitomo. Following the constraints coming from the mechanics of the tracker and in order to guarantee the best placement on the final structures, it was decided to place the sub-components on both faces and to develop six different variants of the circuit (with evident consequences in the mass production as described in the next paragraphs).

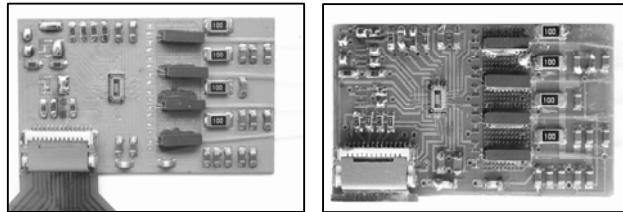


Figure 4. The earliest AOH prototypes in  $\text{Al}_2\text{O}_3$  (left) and FR4 (right). Four prototype laser diodes were mounted on both circuits.

The later prototyping phase was devoted to a fine optimization of the circuit. Two further prototypes AOH were developed and extensively tested accordingly to a qualification programme, described in section IV, based on the system specifications. From the mechanical point of view, the aim was essentially to achieve the right robustness whilst maintaining good ease-of-handling of the AOH. The weak point at that time was the presence of uncovered wire-bonds on both faces (on the LLD, still naked die, and on the laser diodes). For the LLD a thermally conductive “glob-top” approach (Epo-Tek 87-GT) [13] was followed, but the subsequent qualification increased the worries for outgassing phenomena that could not be tolerated by the chip. Eventually, in the prototyping phase, the LLD chip was packaged in a standard  $5 \times 5 \text{mm}^2$  LPCC-32 package so solving the problem of robustness. Concerning the laser diodes instead, it was decided to use an ABS rigid cover (the “hard-cover”) to protect the wire-bonds, coupled with a fibre clamp to provide additional strain relief (Figure 2).

### 3.2 AOH assembly

With the exception of the laser diodes, all the AOH components are SMD. Thus what was required in the first part of the assembly procedure was substantially a standard industrial high-throughput automated process. It is worth observing that, during this stage, particular care was taken with the LLD mounting. Techniques for placement and soldering of a standard LPCC components are obviously well known by the industrial manufacturers, however, in our case, the LLD package had a particular geometry that obstructed the forming of the solder-meniscus. Due to this, a special control of the temperature profile in the solder reflow oven and an x-ray inspection (Figure 5) were implemented to guarantee the appropriate reliability of the assembly phase.

<sup>1</sup> Late AOH used more robust PE-coated fibre instead of acrylate.

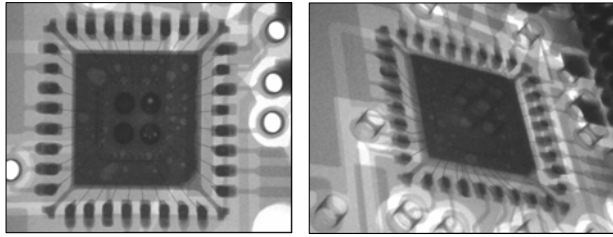


Figure 5. The x-ray inspection was carried out taking two photos for each LLD in order to examine the chip from both a bi-dimensional and spatial view.

The particular characteristics of the laser diodes impose a manual, time consuming, assembly procedure. The devices were first glued on the substrate together with the fibre clamp and cured in an oven (accordingly to the glue specifications). Then wire-bonds wedge-to-wedge (AI) between laser bond-pads and PCB were placed and, finally, the protective hard cover was put and glued to the structure. During the gluing phase also a plastic label (carrying a two-dimensional, machine-readable, QR-code) was manually placed on the PCB for the future classification and tracking. For all the operations epoxy glue (Epo-Tek T7110) [13] was used. This glue had been selected (and tested for rad-hardness) by INFN Perugia during the prototyping phase.

### 3.3 AOH assembly company selection

The company tender had to consider some self-evident starting points. First of all the AOH is a specialized device, to be developed in six different double-faced versions, which requires particular machines and about ten minutes of skilled manual-work, using special purpose-built jigs to make the assembly work (Figure 6). A highly automated production process is not cost-effective in this case, plus the total quantity represented a low volume product. This condition typically favours the medium-sized or smaller assembly companies. Clearly the process must be reliable and stable during the full duration of the project. INFN had to provide training related to proper handling of the fragile optoelectronics components to the manufacturer. Another important point was the price. The cost had to be low but experience has shown that for such specialized devices the quality and the efforts taken by the manufacturer are more important.

Ten Italian companies were contacted in 1998 during the market survey phase. Two ones were selected for preliminary offers and assembly of early prototypes (3 AOH, 1999/2000) and later prototypes (15 AOH, 2000/2001). In July 2002 INFN launched an Italian National Tender and the order was awarded to G&A Engineering [14].

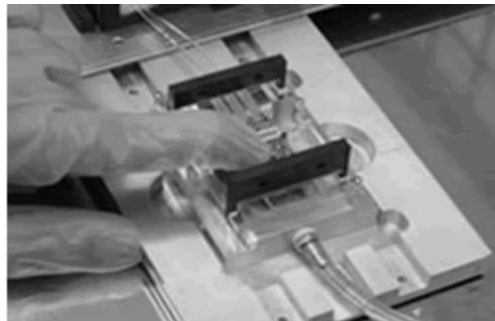


Figure 6. A crucial manual assembly step during the laser and fibre clamp gluing. More than 15 different types of jigs have been used for the mass-production.

## 4 Quality Assurance

### 4.1 Qualification programme

Each single component of the AOH (Figure 7) has gone through its own QA programme. The LLD and optical components have been qualified at CERN [6] [7], while passive components, glues and mechanical parts have been qualified by INFN Perugia [12]. The next step has been the qualification of all the assembled prototype devices to verify both the circuit performances and the manufacturing process in preparation of the mass-production. Moreover, according to a well-defined procedure decided in agreement with the company, during the volume production phase every AOH was checked for correct electrical and optical properties (Figure 8).

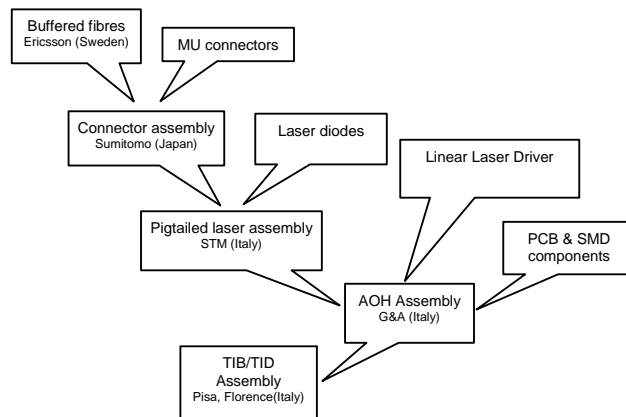


Figure 7. Manufacturing flow of the TIB/TID Analog Optohybrid.

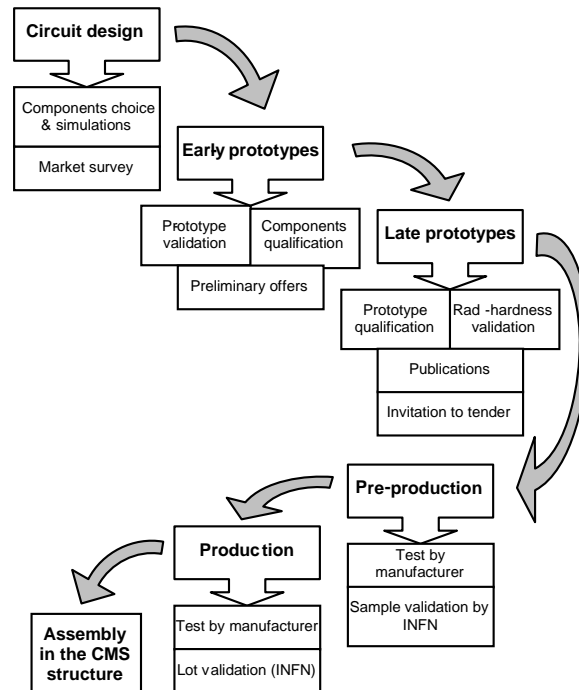


Figure 8. Stages of QA activities: from design to final assembly.

## 4.2 Pre-production qualification

Before reaching the final version, the AOH circuit was refined in a period during which the other components (especially the LLD and the laser diodes) were also subjected to a parallel process of qualification, validation and optimization. Thus the earliest prototypes were essentially devoted to finding the best solutions from mechanical and geometrical points of view according to requirements of the CMS Tracker TIB/TID assembly centres. In particular, on the subsequent AOH prototypes, a wide series of environmental and functionality tests were carried out in order to check that the AOH met the optical link specifications [15].

Environmental tests were made to verify the robustness of the circuit in the harsh operating conditions of the CMS experiment [2]. For this purpose several AOH underwent to a series of thermal cycles (15 cycles lasted 3 hours each with a temperature variation between  $-20^{\circ}\text{C}$  and  $45^{\circ}\text{C}$ ) and long-term measurements in cold conditions (2 days at  $-15^{\circ}\text{C}$ ). AOH were also irradiated (under normal operating conditions) confirming the correct behaviour of the whole circuit [16].

Functionality tests verified the reliability of the circuit in terms of electrical and optical performance. To this aim, the AOH has been qualified both in a stand-alone condition (Figure 9a), reading directly the optical output power, and in a system configuration (Figure 9b), connecting the fibres to a special-purpose receiver (as in the real CMS optical link) and reading the output produced by an electrical input stimulus simulating the typical signal coming out from the front-end detection module.

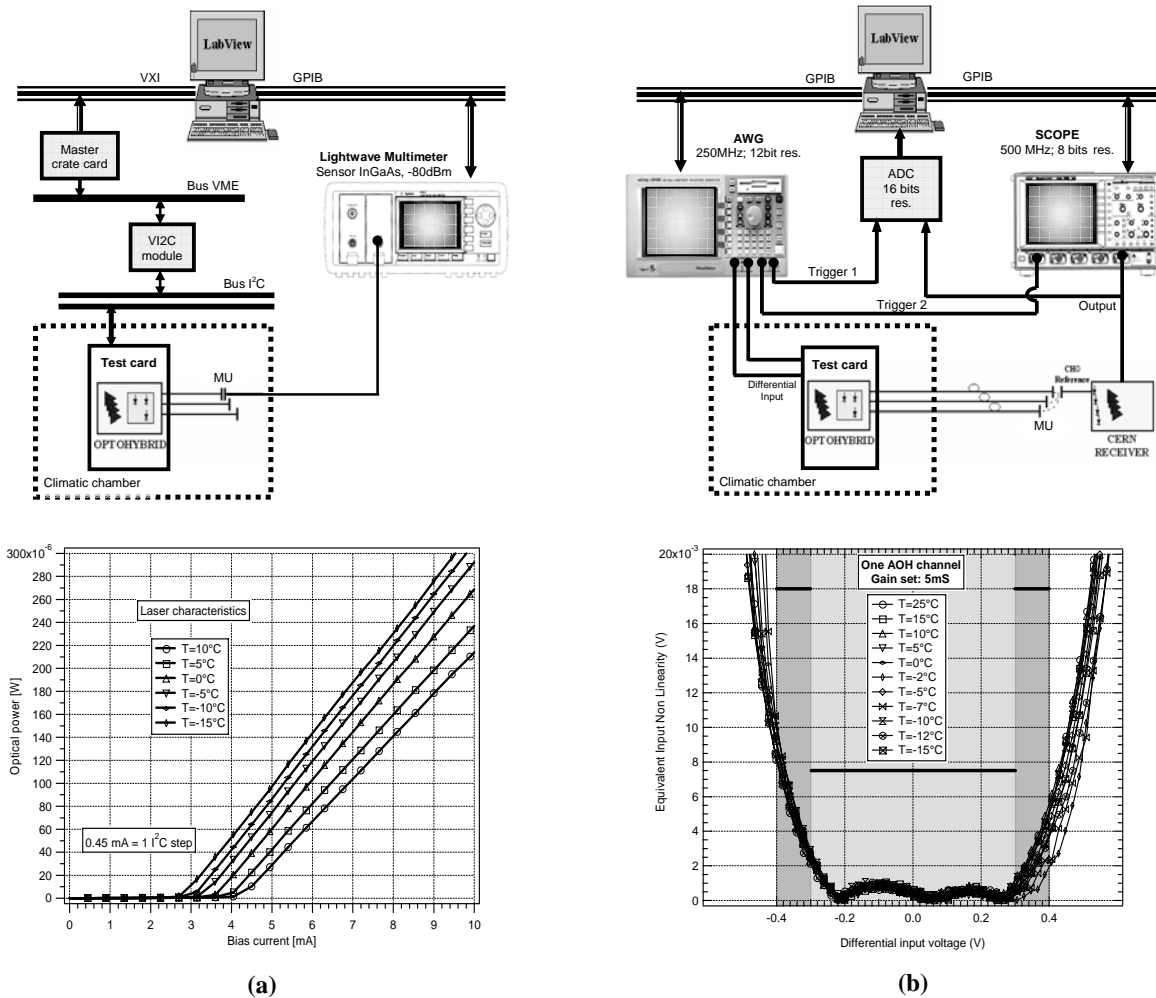


Figure 9. Set-up for the functionality tests of the AOH with typical results. On the left (a) bottom, the laser diodes transfer characteristics versus temperature. On the right (b) bottom, a typical example of the good linearity of the circuits within the operating windows range (black bars represent the upper specification limits).

The results show that the AOH pass the various specifications, in some cases, with a very comfortable margin, with a maximum input range of  $\pm 400\text{mV}$ , an output linearity deviation less than 2%, bandwidth of 120MHz, peak signal to noise ratio of 48dB and a total power dissipation of 120mW (in the typical operating settings). A list of the qualification tests performed is reported in Table 2, while the results details can be found in [17].

### 4.3 Production qualification

The production phase (4290 devices ordered) has been split into two steps: a pre-production stage during which 50 AOHs, in all the topologies, have been produced to validate the industrial assembly process, and a subsequent production stage. During pre-production a training of the company staff was made in order to correctly define the laser and fibre handling procedure during assembly.

Table 2. Functionality and environmental tests performed during the qualification of the AOH circuit.

Specification	Manufacturer	INFN Perugia	Product qualification	Lot acceptance
	Substrate validation	Product validation		
Visual inspection	*	*	*	*
I2C Test	*	*	*	*
Gain		*	*	*
Noise		*	*	*
Integral linearity deviation		*	*	*
Max. operating input voltage range		*	*	*
Input voltage range		*	*	*
Quiescent operating point		*	*	*
Input resistance / decoupling capacitors	*	*	*	*
Bandwidth		*	*	*
Settling time to $\pm 1\%$			*	
Jitter			*	
Skew			*	
Crosstalk			*	
Fibre length (signal propagation time)		*	*	*
Hardware reset	*	*	*	*
Power supply variation		*	*	*
Power supply rejection ratio			*	
Power consumption	*	*	*	*
Magnetic field			*	
Hadronic fluence			*	
Gamma radiation dose			*	
Temperature/Humidity			*	
Ambient temperature	*	*	*	*

For the optical and electrical tests of the AOH circuits, a sophisticated Automated Test Equipment (ATE) was designed and built by HEPHY Vienna for both TIB/TID and TOB/TEC Optohybrids. The test station permits a complete optical and electrical characterisation of the AOH in less than one minute and has been used in both industrial (for each substrate and assembled circuit qualification) and academic (for sample tests) environments.

The production flow is shown in Figure 10. Since the laser diodes are very delicate components and replacement after gluing on to AOH is impossible, the substrate functionality has to be assured before mounting them with a complete set of electrical tests (Substrate Validation). After assembly, every finished AOH has to undergo a

thorough test (Product Validation). During pre-production, INFN Perugia repeated tests on every Optohybrid. On later production lots, a Lot Acceptance test was performed on a sample basis (variable but never less than 10%) to monitor the quality of the production.

At the end of the production in February 2005, the overall yield of the AOH assembly at G&A Engineering was 98% with a throughput rate that remained constant all the time during the production at 400 circuits per month. This good result has made possible especially thanks to the joint efforts between INFN and the company which have been working in the rigorous application of the quality assurance procedure required by ISO 9000 certifications.

In particular, a very big effort was made by INFN concerning the acceptance of the pigtailed laser diodes. A complex incoming inspection/rejection procedure was necessary and this was developed by INFN Perugia, CERN and HEPHY Vienna. The component delivered to INFN were passed through an inspection particular. Various defects were identified, eg. cuts, abrasions, scratches on the fibres coating and bad gluing, and pads scratches on the lasers package. Consequently a visual inspection on 100% of the incoming lasers was made. During the entire production phase, INFN Perugia inspected one by one more than 8000 devices for the entire length of the fibre (2m) and rejected more than 250 diodes<sup>2</sup>, directing only the good ones for the assembly on the circuits.

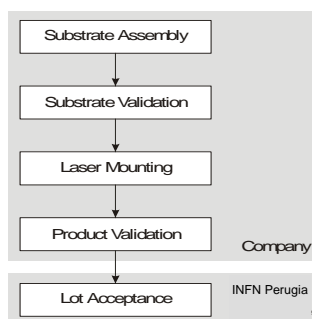


Figure 10. Production flow.

## 5 Statistics and Final Quality Check

The complete record of test measurements performed in the industry has been automatically submitted by the ATE to the central CMS Tracker database in Lyon University, France. This made possible to produce statistical distributions of the AOH electrical and optical parameters. The typical mean values found match the specifications and confirm the good behaviour of the circuit.

The AOH performance was also validated in real final-application conditions during the October 2004 test-beam held at CERN X5. On that occasion, a prototype of the CMS TIB/TID (Figure 11), including 48 AOHs (a total of 120 optical channels), was built and tested at various temperatures during exposure to the particle beam. No problems were encountered during the entire test concerning the handling and robustness of the circuit and the data collected (such as gain, bias variation, linearity and so on) reflect exactly the results found in the laboratory and industrial tests.

<sup>2</sup> The laser diodes inspection, carried out on the first batches, had peaks of 10% of rejected devices. Due to the fact that defects were frequently found on the middle batches too, INFN decided to inspect the 100% of the pigtailed laser diodes.

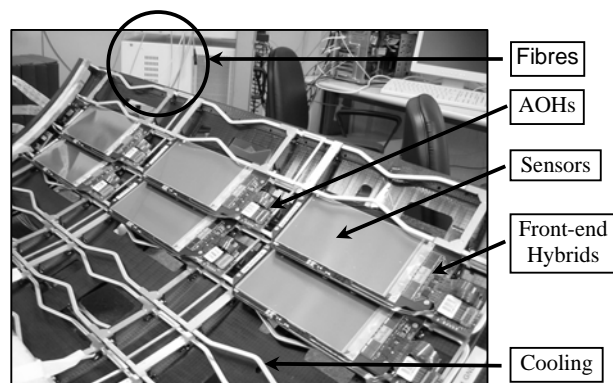


Figure 11. Final test-beam detector structure with AOH mounted on the front-end modules.

## 6 Conclusion

The Analog Optohybrid circuit for the CMS Tracker Inner Barrel and Inner Disks has been successfully developed and produced under the responsibility of the INFN Perugia CMS group.

During the years devoted to the prototyping studies of the project, several activities have been carried out in parallel in collaboration with CERN and HEPHY, in particular the choice, qualification and optimization of the optical link components that represents critical elements in the circuitry. At the end of the prototyping phases the AOH circuit exhibited a very good behaviour meeting mechanically, electrically and optically the requirements of the CMS Tracker optical link specifications.

The handover between INFN Perugia (responsible of the project) and industry (responsible for the production) has been characterized by a continuous synergy as needed for the production of such a specialized device for which a highly automated volume production was not cost-effective. Cost in this case was not synonymous of quality and it was balanced also with other important factors (such as the human skills or the possibility of good interactions with the company) during the market survey and subsequent tender procedure.

At the end of production the very good performance of the AOH circuit has been verified and confirmed analysing the distributions from the whole data collected during assembly in industry. The in-system good performances have been also validated during the last October 2004 test-beam at CERN X5.

Including spares, 4290 circuits have been produced with an overall yield of 98% and a very reliable and stable throughput of 400 pieces per month during all the production phases.

In March 2005 all the devices have been delivered to the CMS assembly centre in Pisa to be assembled in the final structure.

## 7 Acknowledgements

The authors wish to thank the staff of G&A Engineering for the good working relationship and for the important and continuous support to the project. We are also grateful to François Vasey and the CERN CMS Optoelectronics team for their valuable contribution in defining test procedures and HEPHY Vienna group, in particular Markus Friedl (responsible for the test setup project), for their active and friendly collaboration.

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