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Electrical qualification of the pre-production of analogue opto-hybrid circuits for the CMS tracker inner barrel and inner disks

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Abstract

A pre-production of 50 analogue opto-hybrid (AOH) circuits to be used in the front-end electronics of the CMS tracker was extensively tested before the incoming start of the massive production. A total of 4000 AOHs are required for the tracker inner barrel (TIB) and inner disk (TID) construction. The electrical response of the TIB/TID AOH pre-production was tested at 25 °C both for the static and dynamic behavior. A subset of five AOHs was cooled and tested at -10 °C and -15 °C. A passive thermal cycle test from -20 °C to 25 °C was done on a sample of 22 pre-production AOHs, including the previous subset, to measure the mechanical response at possible variations of the nominal tracker temperature of -10 °C. Four AOHs from the subset were also kept at -15 °C for 20 hours in order to check the long-term stability of the response.

The measurements were obtained with the automatic test equipment (ATE) built for the fast qualification during the massive AOH production and with a custom setup dedicated to the additional tests foreseen only in the pre-production phase.

Results of the tests at 25 °C are reported and show the very good agreement with the specifications required for the AOH circuit. No mechanical stress, nor electrical response variations were observed after the passive thermal cycles and the AOH behavior at low temperature was also very good and stable.

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1. The analogue opto-hybrid circuit

The analogue opto-hybrid (AOH) circuit [1] employed in the optical link of the CMS silicon tracker converts the differential input voltage, coming from silicon microstrip detectors and sampled by the APV25 front-end readout chips [2], into analogue optical signals transmitted via single mode optical fibers to the back-end electronics. About 17000 AOH circuits will be used in the tracker and 4000 of them are for the inner barrel and inner disks (TIB/TID AOH).

The TIB/TID AOH circuit is a FR4 (vetronite) substrate with dimensions of 30x22x0.5 mm^3 equipped with one programmable linear laser driver (LLD) chip [3] and two or three laser diodes corresponding to single or double sided detectors (see figure 1). The amplitude of the AOH differential input voltage can be increased by setting the gain of the LLD (hereafter LLD gain). Four values are programmable via I^2C-bus (Philips Semiconductor) and correspond to 5, 7.5, 10 and 12.5 mS. The optical fibers connected to laser diodes are 2 m long in the TIB/TID AOH and end with a MU connector (Diamond MU-S0.6).

The TIB/TID AOH is produced in four different layouts to mate with single side and double side silicon detector modules.

All components in the AOH circuit (laser diodes, LLD, fibers, connectors, passive components, etc.) are resistant to high level of radiation and have been extensively tested [4,5] for this specific requirement. The AOH circuit itself has been also successfully irradiated in June 2002 in the cyclotron at the Forschungszentrum (FZK) in Karlsruhe (Germany) [6].

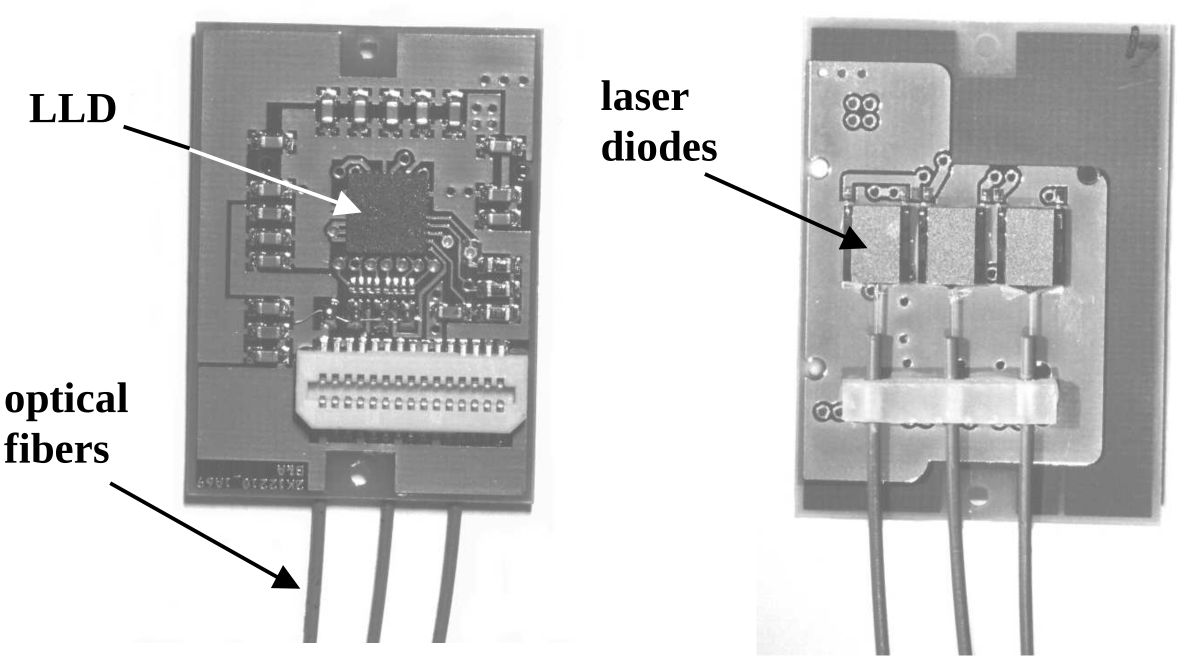


Figure 1. Front side and back side of the TIB/TID analogue opto-hybrid.

2. Electrical qualification

The electrical behavior of the AOH must respect a series of specification values defined by the tracker optical link group of the CMS collaboration [7]. For this reason, a list of tests to be done on the AOH by the manufacturer and by the CMS institute in charge (Perugia for TIB/TID AOH, Vienna for TEC and TOB AOH) has been defined, and is shown in Table I.

In particular, in the first column is reported the test name with the acronym, if any, used in the following of the paper. The tests marked with an asterisk in the second and third columns are under the responsibility of the manufacturer and refer, respectively, to the validation of the substrate before assembling laser diodes (substrate validation), and the validation of the final AOH (product validation). The fourth and fifth columns report the tests to be done by the CMS Institute responsible of the AOH during the qualification, before the start of massive production (product qualification) and during the production itself (lot acceptance). The last column contains the operational specification values for the corresponding test.

Table I

Test type	Manufacturer: Substrate validation	Manufacturer: Product validation	CMS Institute in charge: Product qualification	CMS Institute in charge: Lot acceptance	Operational specifications min	Operational specifications max
Visual inspection	*	*	*	*	-	-
I2C test	*	*	*	*	-	-
Gain [µW/mV] (at 4 LLD gains)		*	*	*	0.13 0.19 0.26 0.32	0.29 0.43 0.58 0.72
Equivalent input noise (EIN) (mV)		*	*	*	-	3
Integral linearity deviation (ILD) [%]		*	*	*	-	3
Max. operating input voltage range [V]		*	*	*	-0.3	0.3
Input voltage range [V]		*	*	*	-0.5	0.5
Quiescent operating point		*	*	*	-	-
Input resistance [kΩ]/ decoupling capacitors [pF]	*	*	*	*	100 -	- 5
Bandwidth [MHz]		*	*	*	90	-
Settling time to ±1% [ns]			*		-	12
Jitter [ns]			*		-	0.5
Skew [ns]			*		-	1.5
Crosstalk [dB]			*		-	-54
Fiber length		*	*	*	-	-
Hardware reset	*	*	*	*	-	-
Power supply variation [V]		*	*	*	2.25	2.7
Power supply rejection ratio (PSRR) [dB]			*		-	-30
Power consumption	*	*	*	*	-	-

Due to the wide variation of the laser diode response with temperature, these operational specifications are referred to measurements at 25 °C. Nevertheless the CMS tracker is foreseen to run at a nominal temperature of -10 °C and the AOH functionality was therefore measured also at -10 °C and -15 °C.

The integral linearity deviation (ILD), gain, equivalent input noise (EIN), bandwidth, crosstalk between channels, jitter, skew and power supply rejection ratio (PSRR) of the 50 pre-production AOHs were tested at 25 °C. A subset of five was cooled at -10 °C and -15 °C and the ILD and EIN were measured at these temperatures.

A sample of 22 pre-production AOHs, including the subset of five, went under 15 passive thermal cycles between -10 °C and 25 °C, where each cycle started and returned at 25 °C in three hours. This test allowed to prove the mechanical reliability of the circuits when quite fast temperature changes occur.

The long term test was performed on four AOHs, which come from the previous tests. They were cooled at -15 °C for 20 hours and then re-tested to check the stability of the response.

During the tests at 25 °C and at low temperature the AOH circuits were always placed into a programmable climatic chamber Vötsch VT4010. The same chamber was used for thermal cycles and long term test.

Two complementary setups were used to test the pre-production AOHs.

3. Automatic Test Equipment setup

The automatic test equipment (ATE) shown in figure 2 was designed and build by the CMS collaboration (HEPHY -Vienna) [8] for the fast qualification of the AOHs in the manufacturer industry and in the Institutes in charge during the AOH massive production phase. The test procedure is automatic and the test results are downloaded in the CMS tracker database [9].

The VME crate shown in the left of fig. 2 contains a VME crate controller and a dedicated VME module for the AOH. This VME module is the core of the test system since it contains all logic and analogue circuits to control, drive and reads back data from the device under test. Here the AOH optical output is converted into electrical by a 4-way optical-to-electrical (O/E) receiver build at CERN for test purposes [10].

The system made up of the AOH read by the 4-way receiver is called optical link.

The VME module is connected to the front-end board (in front of the crate in fig. 2), which consists of a mechanical jig to hold the AOH delivery box, the optical connector patch panel and the electronic board housing some drivers and amplifiers and a temperature sensor.

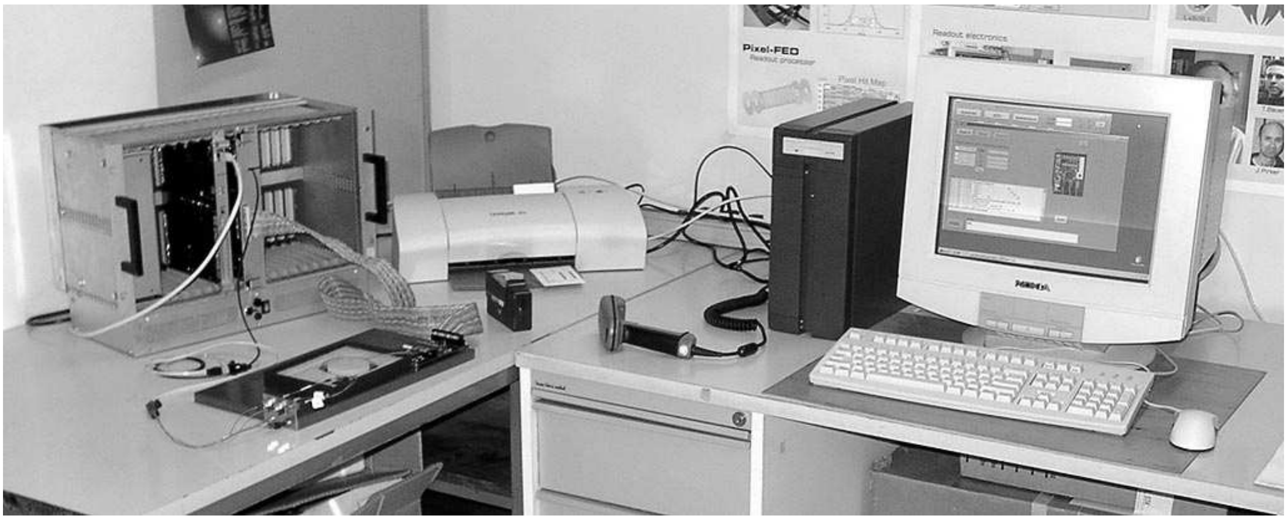


Figure 2. Automatic test setup for the electrical and optical qualification of the AOH.

The front-end board is placed in the climatic chamber, but since it is done with commercial off-the-shelf (COTS) components, its functionality is limited to approximately -5 °C, therefore the ATE was used only in the qualification at 25 °C.

The PC running the test software is connected to the VME system by a dedicated Ethernet link.

The identification of the AOH circuit and of the single optical fibers is done reading their QR labels (2D barcode) with the scanner.

The inkjet printer produces self-adhesive labels to be attached on the AOH box after the test. The information provided by the labels includes the type of AOH (TIB/TID in our case), fiber length, number of lasers, operator, date, barcode and a brief description of the test result.

The test software is written in the National Instruments LabWindows/CVI environment. During the test, the software checks whether the measured values are in the allowed range, otherwise a failure flag appears and the AOH is marked as rejected.

A long sequence of electrical and optical tests is done automatically by the setup, but only the ILD, EIN, gain and bandwidth results are reported in this paper.

4. Custom Test setup

The second setup is a custom configuration of instruments of the laboratory equipment in INFN Perugia and is shown in figure 3.

The front-end electronics is located inside the climatic chamber and is built with military components in order to work also at low temperatures, therefore this custom setup was used also in the qualification at low temperature (-10 °C and -15 °C).

The CERN 4-way O/E receiver is placed outside the climatic chamber, like in the ATE setup.

The VME based I^2C module communicates with the programmable LLD on the AOH to set the pre-bias current of the lasers and the LLD gain. The pre-bias current is the minimum bias current needed by the laser diode to be about 1 mA above the threshold, in the linearity response range.

The pre-bias current and ILD were measured by connecting the 2-channel Tektronix AWG (Arbitrary Waveform Generator) 2021 to the differential AOH input, and reading the electrical output with a National Instruments 16 bit ADC.

The EIN was measured by connecting the electrical output to the LeCroy LT342 scope.

The crosstalk, bandwidth, jitter and skew were measured with the input given by the pulse generator Agilent 81110A and the output read by the scope. The jitter and skew measurements were obtained by using a fast O/E converter (Opto Speed PDMH40A), in order to have a higher speed response and to eliminate the jitter of the CERN 4-way receiver.

The spectrum analyzer HP 4396 was used to measure the power supply rejection ratio.

On the right of the fig. 3 is shown the climatic chamber that maintains the AOH and the front-end board at the temperature set by the operator with variations lower than 1 °C.

Figure 3. Custom test setup for the electrical qualification of the AOH. On the right is visible the climatic chamber containing the front-end board and the AOH.

5. Test results at 25 °C

The 50 pre-production AOHs were tested at 25 °C with both setups.

In particular, the ILD, EIN, gain and bandwidth were measured with the ATE, while crosstalk, jitter, skew and PSRR with the custom setup. The results are reported together with the operational specification values for the measured characteristics. Note that these specifications are very stringent and certify an optimal AOH performance during the CMS lifetime.

5.1 Tests with ATE

The ATE starts the electrical test with the determination of the pre-bias current for each laser diode (channel) at the four LLD gain settings. Once the laser diode is biased, the setup measures the output transfer characteristic by setting the differential input voltage to 25 equally spaced values in the range -0.5 to 0.5 V. The integral linearity deviation (ILD), shown in figure 4, is calculated by fitting the output transfer characteristic of each AOH channel in a linear operation window (-0.35, +0.35 V) of the input voltage. For each output power measurement an average value is calculated from 128 consecutive samples. The ILD is the percentage of deviation from the calculated linear regression. The results in fig. 4 refer to the four LLD gain settings and show an ILD mean value of about 0.7%, very far from the upper limit of 3% required by the specifications reported in Table I.

The AOH gain, shown in figure 5, is the slope of the upper mentioned linear fit. The four groups of points represent the gain measured on each channel of the 50 AOHs at the four LLD gain settings. The upper and lower limits for each LLD gain are also reported in the graph and show that the measurements are well inside the specifications given for this parameter.

The equivalent input noise (EIN) of the optical link is measured in the same input voltage range -0.5 to 0.5 V as ILD only for the highest LLD gain of 12.5 mS. This corresponds to the worst case among the LLD gains. The rms value, noise(V_i), of the distribution of 128 consecutive samples taken for the output power at each intermediate input voltage V_i is measured. The noise(Vi) is divided by the measured optical link gain to obtain EIN(V_i) and the average value in the range -0.35 to 0.35 V for N equally spaced values is EIN:

$$\mathrm{EIN}(V_i) = \frac{\mathrm{noise}(V_i)}{\mathrm{gain}}$$

$$EIN = \frac{\sum_i EIN(V_i)}{N}$$

The distribution of EIN values measured at each channel of the 50 AOHs is shown in figure 6. The mean value of EIN is about 1 mV, while the upper limit given by the specifications in Table I is 3 mV.

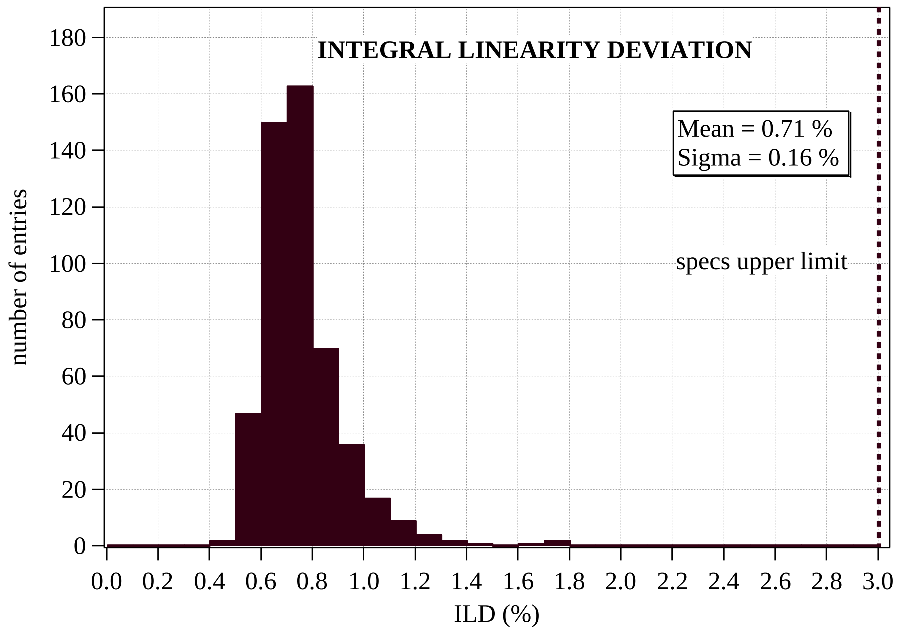


Figure 4. Distribution of the integral linearity deviation of the 50 pre-production AOHs.

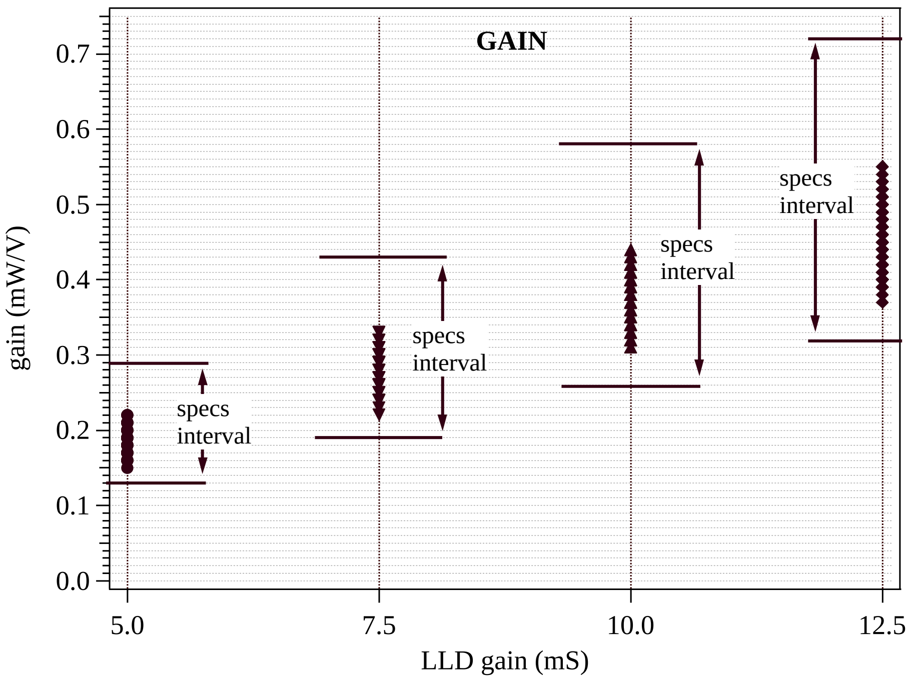


Figure 5. Gain measured on the 50 AOHs as a function of the linear laser driver gain. The horizontal lines represent the limits given by the specification requirements.

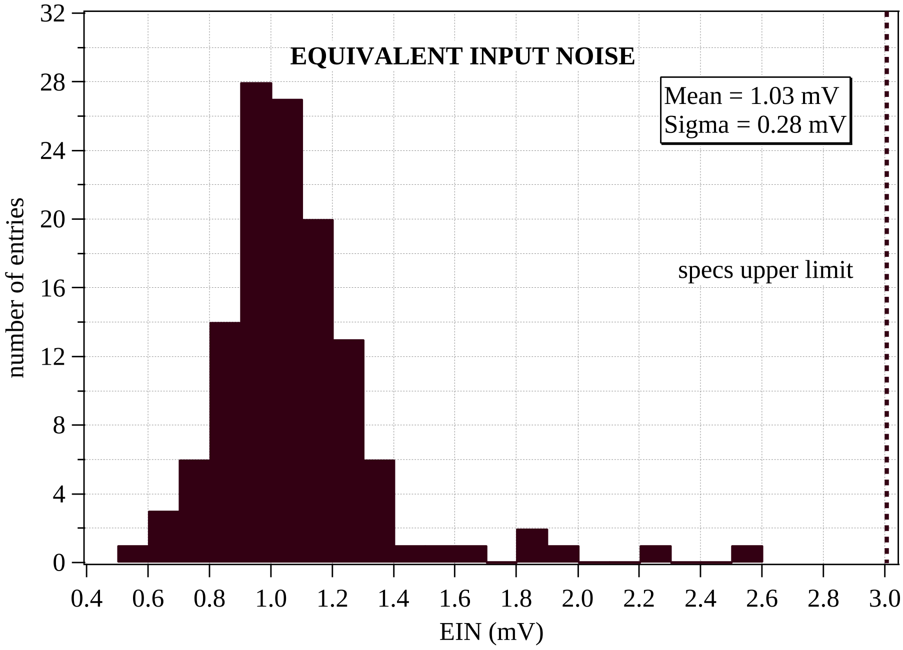


Figure 6. Distribution of equivalent input noise on all channels of the 50 AOHs. The LLD gain was set to its highest value (12.5 mS).

The bandwidth (BW) measurement is in fact a rise time (t_r) measurement of the output of a square wave applied to the input of each AOH channel. Then an experimental relationship is applied to obtain the BW:

$$\mathrm{BW}\,(GHz) = \frac{0.338}{\mathrm{t_r}\,(ns)}$$

The distribution of the bandwidth measurements is shown in figure 7.

The mean value is about 127 MHz while the lower limit fixed by the specifications reported in Table I is at 90 MHz.

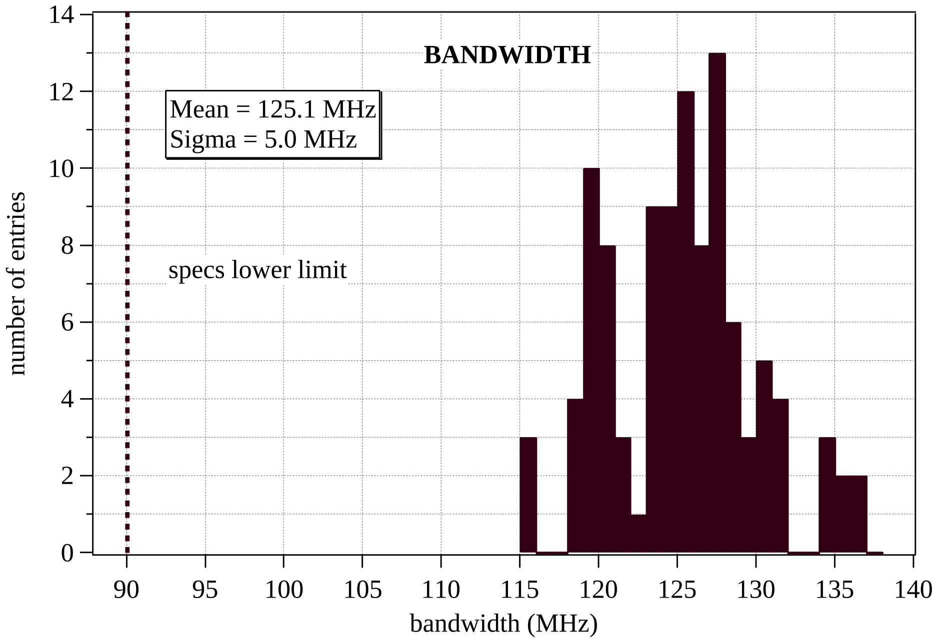


Figure 7. Bandwidth distribution of 50 AOHs. The dotted line in the left of the graph represents the lower limit allowed.

5.2 Tests with custom setup

The custom setup is used to perform the additional tests foreseen during the production qualification (see Table I). These tests will be no more done in the production phase, since their results are mainly related to the circuit layout. Here are reported the results on dynamic electrical behavior like crosstalk, jitter, skew and the PSRR test.

The crosstalk (CT) between two channels i and j is defined as the relative feedthrough from channel i to channel j at sampling time of 20 ns when an ideal (rise time of the order of 0.8 ns) step is injected into channel i:

$$\mathrm{CT} = 20\log\left|\frac{\mathrm{Output}_j}{\mathrm{Output}_i}\right|_{20\ \mathrm{ns}}$$

The results of crosstalk measurement on the 50 pre-production AOHs is reported in figure 8.

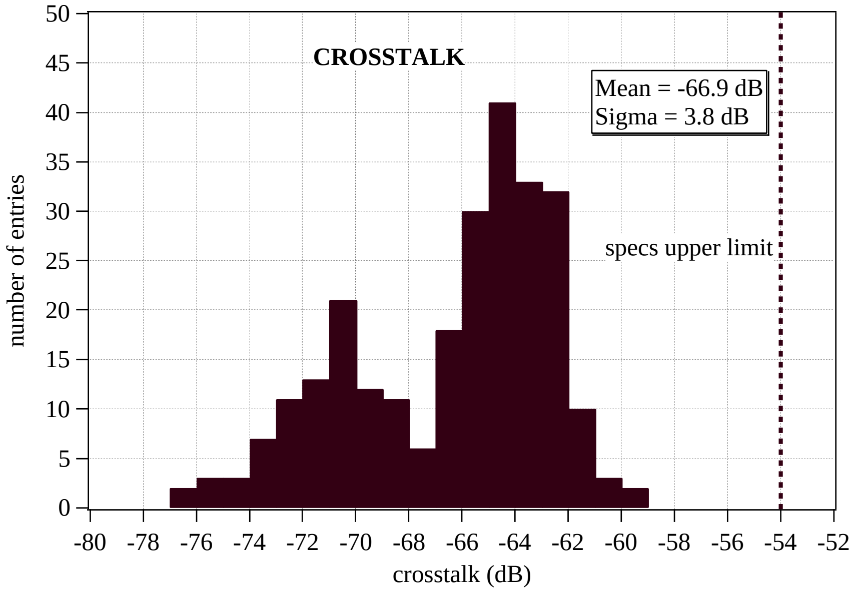


Figure 8. Crosstalk measured in the 50 pre-production AOHs.

The two peaks in the plot depend on the relative distance between the traces corresponding to the channels in the AOH layout. The upper limit allowed of -54 dB is well above the measured values.

The jitter is, in general, the short-term instability of one edge relative to a reference edge. The reference edge is the trailing edge of the input signal used as trigger. Here the jitter is defined as the rms deviation of the time t_{50} required for a step response signal to reach 50 % of its amplitude and $\overline{t_{50}}$ is the average value:

$$\mathrm{jitter} = \sqrt{\left(t_{50} - \overline{t_{50}}\right)^2}\ .$$

The measurement has been done with the fast O/E converter (Opto Speed PDMH40A), the Agilent 81110A pulse generator (rise time 0.8 ns, frequency 5 MHz, differential amplitude 600 mV) and the Lecroy LT342 scope.

Figure 9 shows an example of the scope display with the input signal as reference edge also used as trigger, and the signal from the laser diode converted from optical to electrical by the O/E converter. The jitter was measured with the scope function Δdly (highlighted by the circle) that calculates the difference in time between the two signals t_{50}. The sigma of the time distribution represents the jitter (in the second circle).

The distribution of the jitter measured for all channels of the pre-production AOHs is shown in figure 10. Its mean value is about one order of magnitude less respect to the limit of 0.5 ns given by the operational specifications.

The skew measurement is strictly related to the jitter measurement. It is calculated offline using the average value of Δdly and calculating the difference between $\overline{t_{50}}$ for each couple of channels.

The skew between channels i and j is defined as:

$$\text{skew} = \left|\overline{t_{50,i}} - \overline{t_{50,j}}\right|$$

The skew measured on all AOH channels is shown by the histogram in figure 11. Even for this measurement the upper limit of 1.5 ns is very far from the distribution.

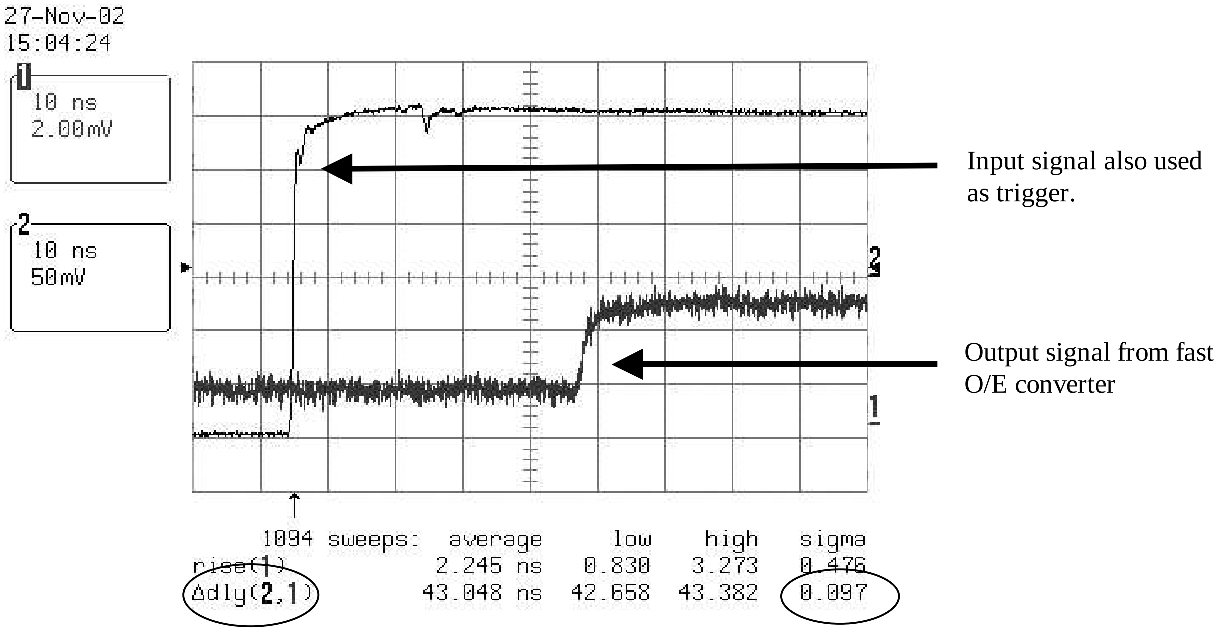


Figure 9. Scope display showing the input step signal (channel 2 of the scope) also used as trigger and the output signal from the AOH laser diode (channel 1 of the scope). The two circles highlight the scope function Δdly used and a typical value measured for the sigma.

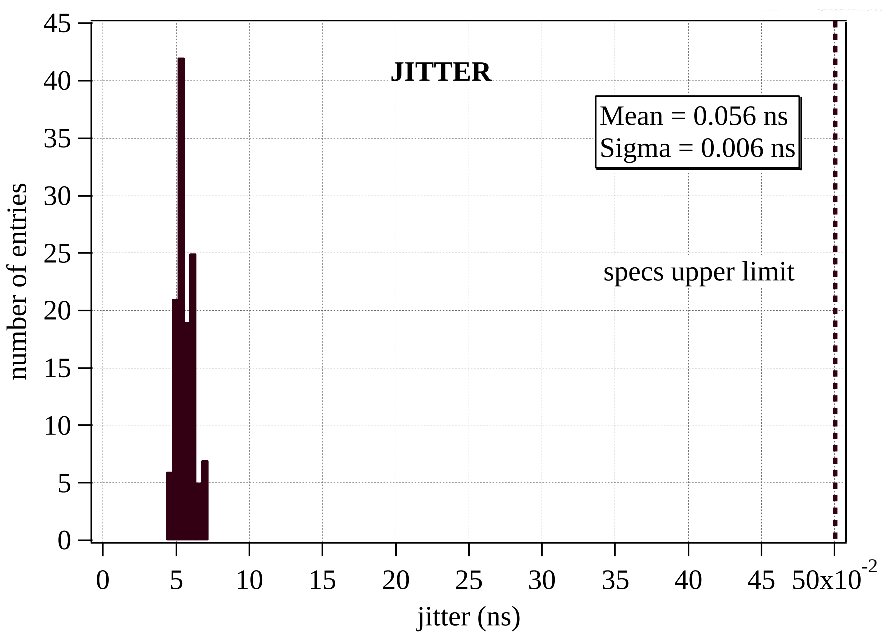


Figure 10. Distribution of the jitter measured in the 50 pre-production AOHs.

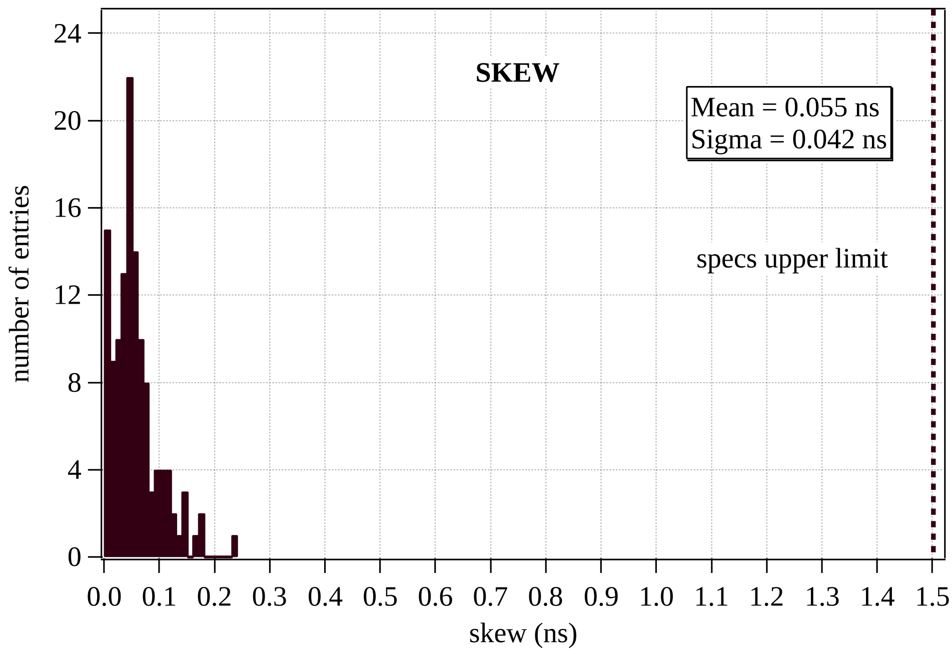


Figure 11. Distribution of the skew measured in the 50 pre-production AOHs.

The power supply rejection ratio (PSRR) is the capability of rejecting the noise contribution on the AOH output signal caused by the power supply lines. It is defined as follows:

$$PSRR = 20\log_{10} (V_{input}/V_{pow\_supply})$$

where V_{pow_supply} is the amplitude of a noise voltage superimposed to the supply voltage and V_{input} is the amplitude of an input voltage that produces the same effect of V_{pow_supply} at the AOH output in terms of power. The PSRR was calculated for both supply voltages (V_{dd}=+1.25 V and V_{ss}=-1.25 V).

The PSRR measurement is divided into two steps. A scheme of the setup used in the first measurement step is shown in figure 12.

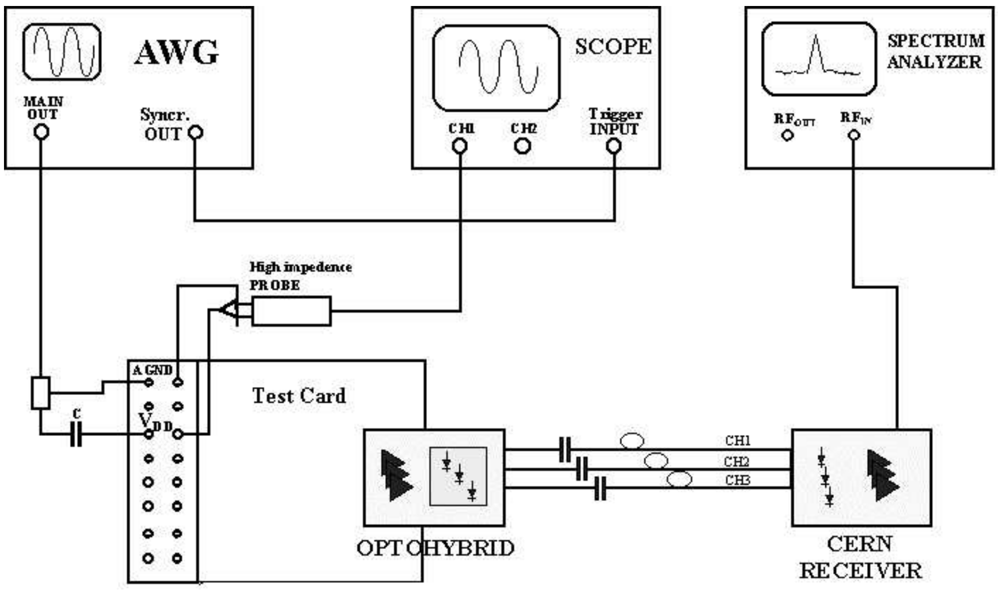


Figure 12. Scheme of the setup used to perform the first step in the PSRR measurement.

The noise on the power supply lines can be generic signal within a given frequency interval. In order to separate each frequency contribution we used the AWG to generate sine waves at different frequencies in the interval 1-50 MHz.

These sinusoids are injected in the positive voltage supply V_{dd} = +1.25 (the procedure has to be repeated for V_{ss}) by an AC coupling. An high impedance probe was used to read the noise voltage after the capacitor C (see fig. 12), in order to measure the coupled voltage. This voltage is indicated as V_{pow_supply}. Reasonable values for V_{pow_supply} are included between a few millivolts and a few dozens of millivolts.

The power (in dBm) of signals for each frequency at the AOH output was measured by the spectrum analyzer.

In the second step we found the input signal V_{input} (one for each value of V_{pow_supply} measured) that produces, at the AOH output, the same results in terms of power. Unfortunately, the AWG used cannot generate a signal with an amplitude so small, therefore it was necessary to operate in a different way, i.e. calculate the power input-output characteristic and extrapolate the required value. Figure 13 shows the scheme of the setup for this second measurement step.

A sinusoidal signal of frequency 5 MHz was injected in each single-ended AOH input. This value of frequency has been taken as a reference value, since we assumed the amplitude of the output frequency response flat in the range of interest (1-50 MHz).

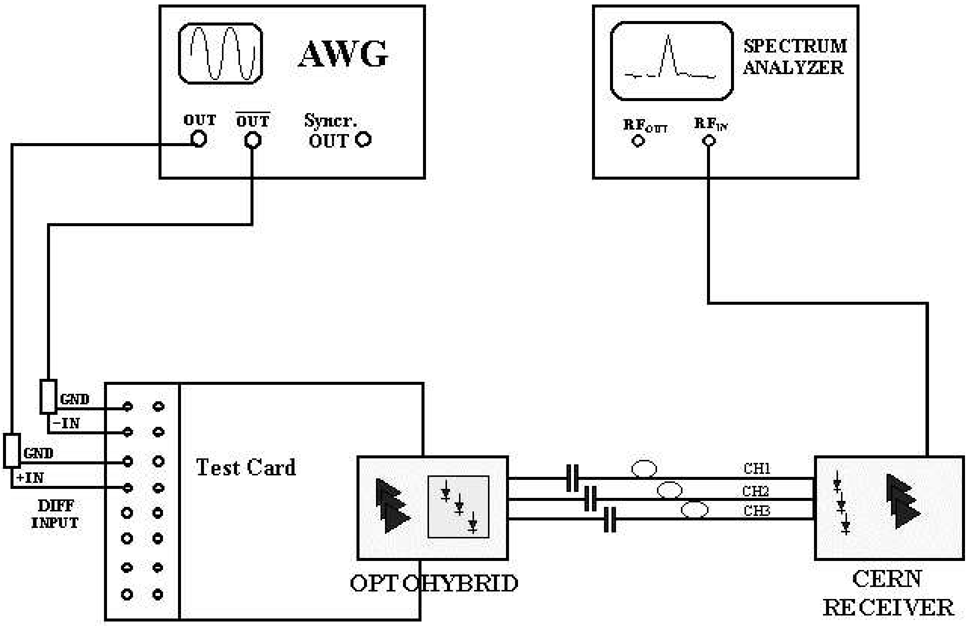


Figure 13. Scheme of the setup used to perform the second step in the PSRR measurement.

The amplitude of the differential input signal was varied from 100 mV to 600 mV. For each amplitude we obtained the corresponding power from the spectrum analyzer. A linear regression of the measured power permitted to determine which voltage value (V_{input}) corresponds to the power of noise (V_{pow_supply}). Then the PSRR was calculated by using the formula reported above. In figure 14 are shown the results of the PSRR measured on V_{dd} and V_{ss}, respectively. In the second histogram, related to V_{ss}, one of the measurements was equal to the operational specification value of -30 dB, while the others are under the limit.

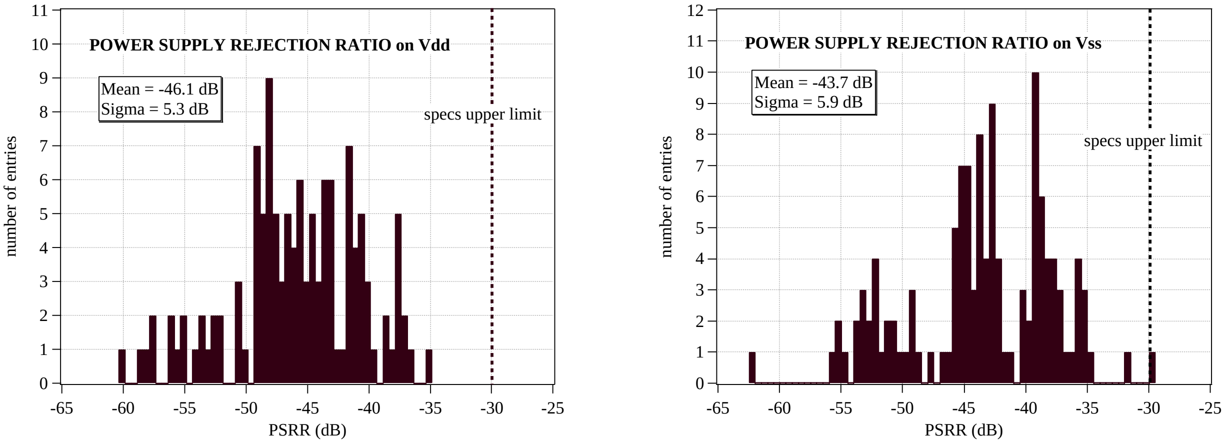


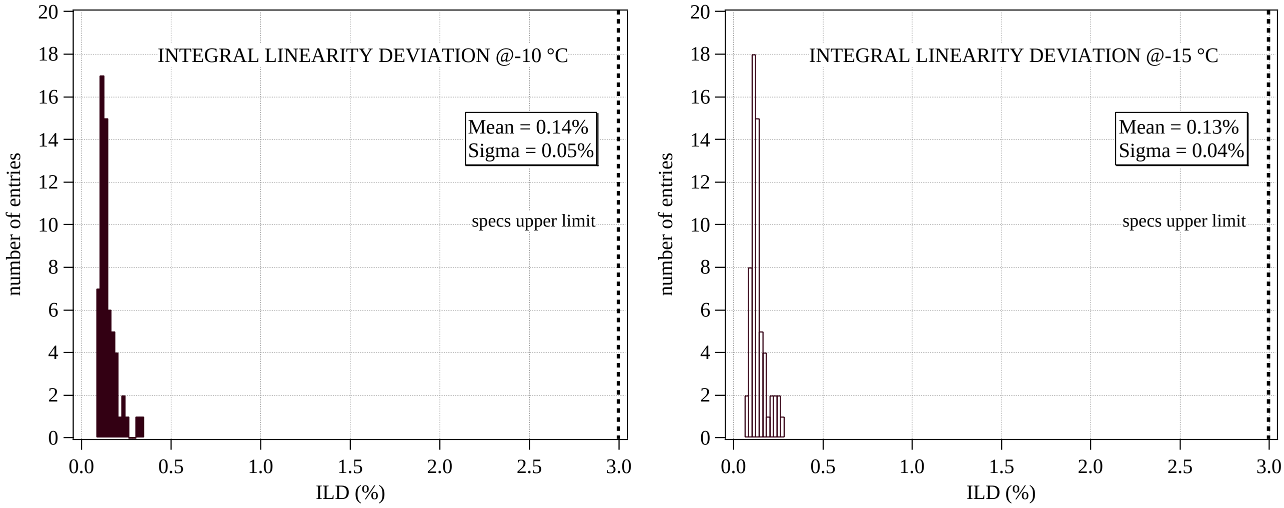
Figure 14. Distribution of the PSRR values measured on V_{dd} and V_{ss} for the 50 pre-production AOHs.

6. Tests at low temperature

The qualification of the AOH pre-production at low temperature was divided in three phases: low temperature response, passive thermal cycles and long term test.

6.1 Low temperature response

The test at low temperature was done with the custom setup. A subset of five pre-production AOHs was cooled at -10 °C and -15 °C and the electrical static response (ILD and EIN) was measured. The ILD is reported in figure 15 (a) and (b) at -10 °C and -15 °C, respectively.



(a) (b)

Figure 15. Integral linearity deviation measured on five pre-production AOH at -10 °C (a) and -15 °C (b).

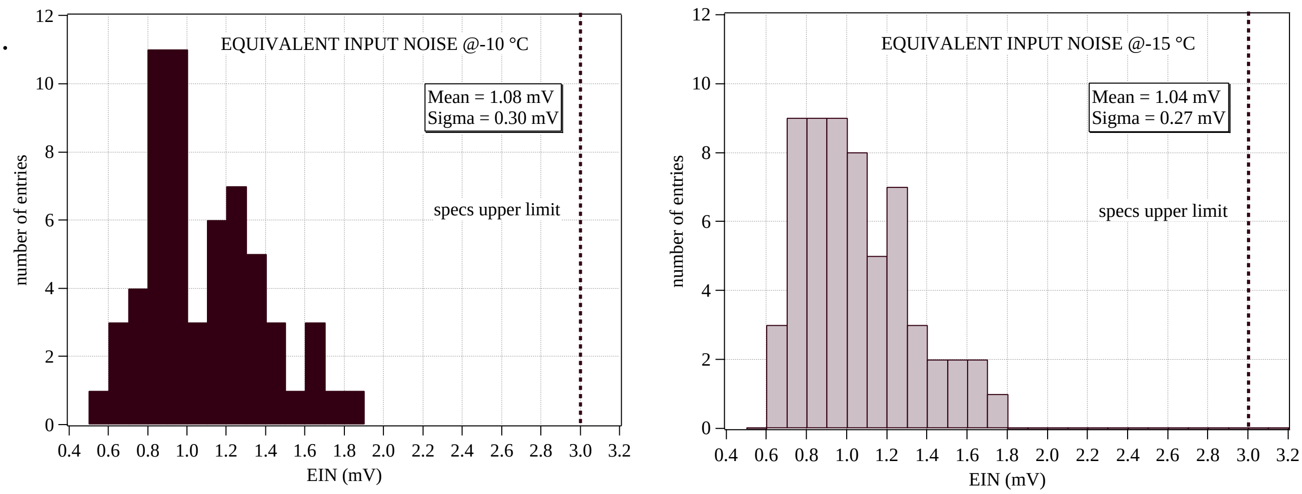
Both the two distributions are very far from the limit of 3% given by the specifications in Table I.

The comparison with the ILD measured at 25 °C (see fig. 1) shows a decrease of about a factor 4. Two contributions are mainly responsible of this behavior.

The first is the use of the custom setup that allows to wait for the heating up of the laser diode after the bias operation. Once the laser diode heats up, its light output reduces until it becomes quite stable after typically three minutes. In a fast qualification, like that foreseen in the production phase, the measurement is taken while the light output of the laser diode is still decreasing therefore increasing the integral linearity deviation.

The second contribution is the decrease of ILD with the temperature. Our estimate, based on previous measurements, is that the ILD mean value decreases of about 15% from 25 °C down to -15 °C.

The EIN was also measured with the custom setup and in figure 16 (a) and (b) are shown the results obtained at -10 °C and -15 °C. The two distributions are very similar to that measured at 25 °C (see fig. 6).



(a) (b)

Figure 16. Equivalent input noise measured on five pre-production AOHs at -10 °C (a) and -15 °C (b).

6.2 Passive thermal cycles

To check the mechanical reliability of the pre-production AOHs, a sample of 22 went under passive thermal cycle between of -20 °C and 25 °C. These two temperatures are reachable in the tracker when the cooling system is not working at the nominal temperature of -10 °C. In the pre-production sample thermally cycled were also included the five AOHs already tested at low temperatures. The circuits were placed in their delivery boxes in the climatic chamber without applying any bias. The duration of each thermal cycle, starting and returning at 25°C was set to three hours, accordingly with the manufacturer specifications regarding the limit of the temperature variation for laser diodes. The cycle was repeated for 15 times and the AOHs were measured again at 25 °C after this test. No changes in both ILD and EIN were observed after the test and results are not reported.

6.3 Long term test

The stability of the AOH response at low temperature was measured for 20 hours at -15 °C on four pre-production AOHs already tested at low temperature and thermally cycled. In figure 17 is shown the temperature decrease registered by the climatic chamber during the cooling down to -15 °C of the AOH circuit. The rate of decrease is about 2.5 min/°C with short intervals corresponding to 10 °C, 5 °C, 0 °C, -5 °C and -10 °C, when the AOH functionality was quickly tested by reading the output light power with the Agilent 81632 lightwave multimeter.

After 20 hours at -15 °C and before the ramp up to 25 °C the four AOHs were tested with the custom setup and both ILD and EIN were measured. The results are reported in figure 18 and 19, respectively.

The results are the same of those measured at the same temperature before the long term test. Note, that the AOHs tested belong to the sample thermally cycled.

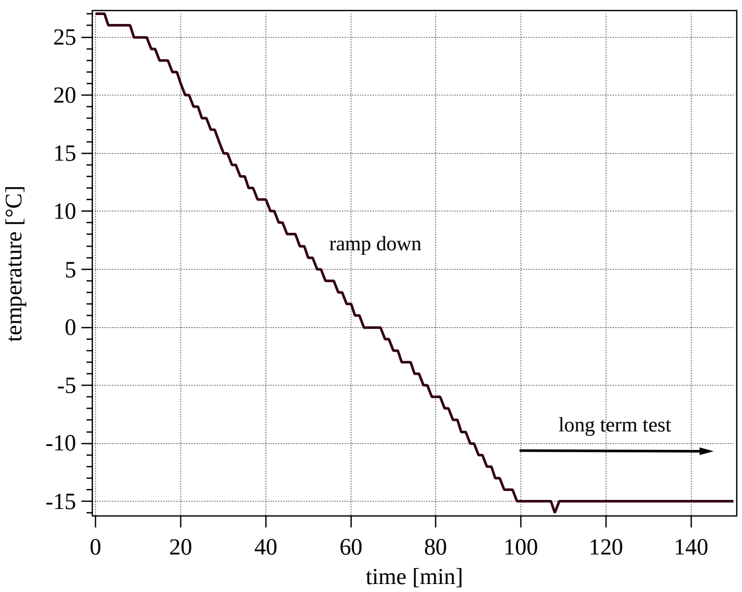


Figure 17. Temperature decrease as a function of time during the cooling of the long term test. The slope of the ramp corresponds to about 2.5 min/°C.

7. Conclusions

The electrical qualification at 25 °C of the pre-production of 50 analogue opto-hybrid circuits gave excellent results, according to the specifications limits required by the tracker optical link group.

Electrical tests at -10 °C and -15 °C, near the nominal tracker operating temperature, have shown that the AOH still works perfectly.

Passive thermal cycles performed on the AOH circuit have demonstrated its mechanical reliability in conditions of quite fast temperature variations.

The permanence at -15 °C for 20 hours has shown that the AOH behavior is the same measured before the test.

The results presented in this paper certified the AOH circuit as ready for the massive. production phase.

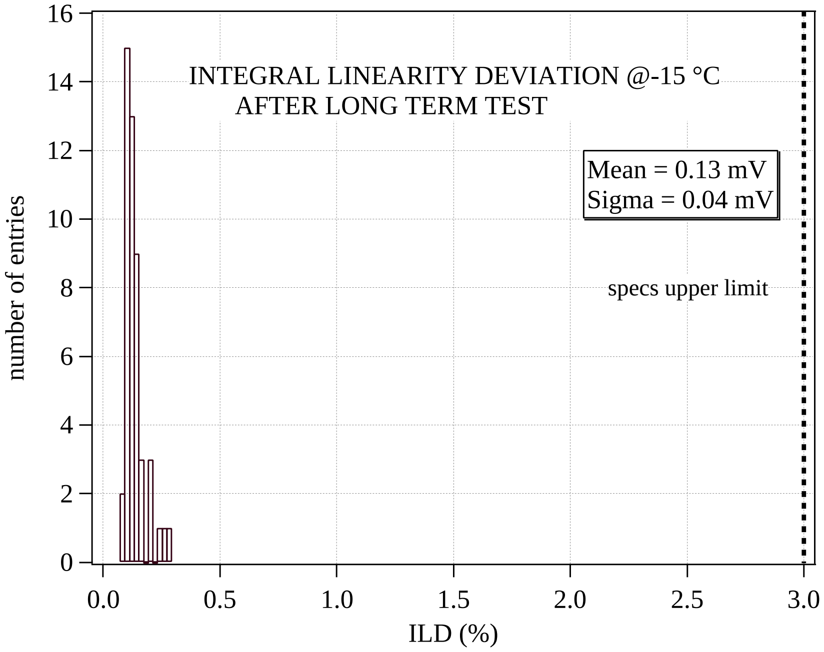


Figure 18. Integral linearity deviation of four AOHs measured at -15 °C, after the long term test.

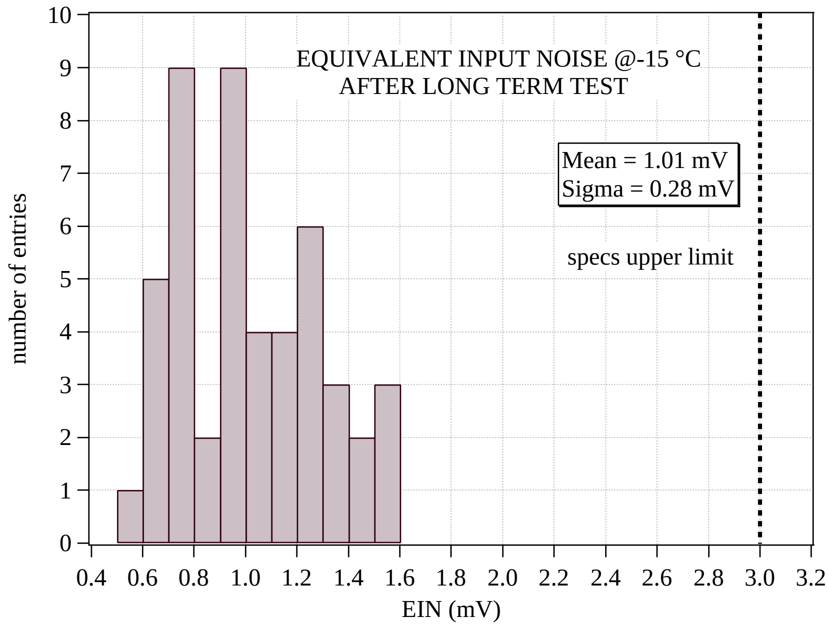


Figure 19. Equivalent input noise of four AOHs measured at -15 °C, after the long term test.

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