Status of the Environmental Quality Assurance Programme for Lasers in Optical Links for Readout and Control Systems in CMS.

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Abstract

The status of the pre-production and production QA programme is reviewed for the environmental compliance tests of lasers to be used in the optical link systems in the CMS Tracker, ECAL, Pixels and Preshower. Three advance validation tests of seven wafer lots of lasers have now been made with very few failures, leading to the acceptance of 35000 lasers for final production.

I. INTRODUCTION

Three different optical link systems are being developed at CERN[1] for CMS: Tracker and Pixel analogue readout links, in collaboration with HEPHI Vienna and INFN Perugia groups, fast digital links for ECAL and Preshower, in collaboration with the University of Minnesota group, and slow digital control links for all of these sub-systems.

The same type of 1310nm InGaAsP/InP multi-quantum-well edge-emitting laser transmitters will be used in all the three different link systems, totaling over fifty thousand lasers, as shown in Table 1. These lasers are based on commercially available off-the-shelf (COTS) devices: the laser diodes are manufactured by Mitsubishi and then packaged and supplied by ST Microelectronics, using a technique and silicon submount component that are both used in similar laser products.

As the lasers are situated at the front-end, within the CMS sub-detector systems, they will be exposed to a harsh radiation environment: up to 2×10^{14}particles/cm^2 and ionising doses up to 100kGy over the expected 10 year lifetime of the CMS experiment[2]. The particle fluence at the innermost parts of CMS is dominated by pions and photons, with energies ~300MeV, and by ~1MeV neutrons at greater radii from the beam-line.

Since the lasers chosen for these links are COTS there is no guarantee of radiation hardness provided by the manufacturer. An 'Advance Validation Test' (AVT), outlined in Ref [3], has therefore been devised to validate laser wafer lots for use in CMS prior to assembly of a large quantity of transmitters from those wafers.

For commercial reasons, only 3000 laser chips are guaranteed to be available from a given wafer, therefore a series of AVTs, in step with the laser packaging at ST are being carried out. To date, three AVTs (AVT 0, AVT 1, AVT 2) have validated around 35000 lasers from 7 different wafers. AVT 3 will take place later in 2003 and at least one more AVT is expected to be necessary in 2004.

The AVT tests are just part of a broader Quality Assurance (QA) programme[4,5] on lasers and other link components which has been defined in order to guarantee that the final links meet the specified performance and are produced on schedule.

In this paper we present details of the AVT procedure and a summary of results from three AVT's to date.

Table 1: Approximate number of lasers that will be used in the diferent parts of CMS.[1]

Destination of lasers under AVT tests	Number of lasers
Tracker analogue readout	37 000
Ecal readout	9 000
Pixels readout	1 500
Preshower readout	1 200
Digital Control (all subdetectors)	2 800

II. LASER AVT PROCEDURE

The AVT procedure is outlined in Fig 1. ST samples 30 lasers at random from each wafer lot supplied by Mistubishi. The lasers are mounted on silicon submounts, burned-in and then packaged in their intended final form. This is a very compact 'Laser-pill' package, that is non-magnetic and has a single-mode fibre pigtail and MU connector already qualified by CERN for radiation resistance. The laser package does not include any other components, such as lenses, that could be degraded by radiation damage.

The test conditions for the AVTs are summarized in Table 2. The procedure of AVT can be divided into several stages (Steps A to D). Steps A and B are measurements of damage and annealing with gamma and then neutron sources respectively. The lasers are irradiated at room temperature, with gamma rays and then neutrons, up to the worst-case equivalent doses and fluences inside CMS.

[1] The actual number of lasers validated in AVTs could be significantly larger than these values, depending upon the yield of the transmitter assembly process.

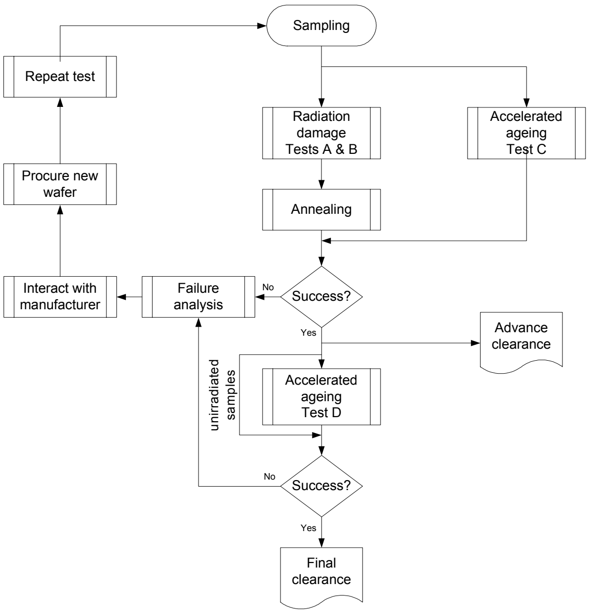

Figure 1: Flow chart of the laser AVT procedure.

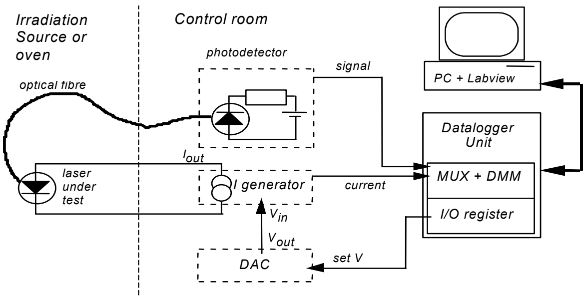

Figure 2: Control and data-acquisition system for in-situ measurement of laser L-I characteristics during irradiation or aging. Up to 60 lasers are tested in parallel.

^{60}Co-gamma facilities at the RITA facility of the SCK-CEN laboratory in Mol, Belgium (for tests with in-situ monitoring) and Ionisos, France (for passive tests) are used to expose the lasers to a total gamma dose of 100kGy (±10%). This dose was uniform across the samples and stable over the irradiation period of several days.

Neutron irradiation is made at the Cyclotron Research Centre (CRC) at Louvain-La-Neuve, in Belgium. An intense and constant flux of neutrons is available with an average energy of ~20MeV, from a beryllium target bombarded with 50 MeV deuterons.

Steps C and D involve accelerated aging. The devices are operated at 80°C and 60mA for a target time period of at least 1000 hours to measure any potential wearout degradation. Step C studies the ten unirradiated lasers from each wafer-lot, whilst Step D, covers the twenty lasers irradiated in Steps A and B. The inclusion of both irradiated and unirradiated samples in the aging tests allows a check to be made for any degradation that might be related to the radiation damage.

In most of these test steps, the lasers were connected both optically and electrically, as in Fig. 2. This allowed measurement of the radiation damage and annealing, as well as aging-related degradation in-situ. As will be demonstrated later, the gamma irradiation has little influence on the laser characteristics; therefore to spare resources it was decided not to make in-situ measurements in gamma tests after AVT1.

In the neutron irradiation however the radiation damage is significant and in-situ monitoring is necessary to allow useful comparison of data with results from earlier tests.

The acceptance criteria for the wafer lot in the AVT are that 95% of the samples tested should remain within all the operating specifications for the (Tracker analogue) optical link system, under the worst-cases of radiation damage exposure, and any additional wearout degradation, when extrapolating to the full 10 year lifetime of the links.

Any failures are analysed post-mortem, in order to diagnose the cause of failure. Only failures that were intrinsic to the device-under-test are counted in the results of the AVT.

Table 2: Experimental conditions for the radiation damage, annealing and aging studies

Test step	No. laser samples per wafer	Dose or particle fluence averaged over devices (±10%)	Irrad time (hrs)	Monitored annealing time (hrs)	Test conditions (bias, temperature)
A	20	100kGy (^{60}Co-γ)	48	12 (AVT 0, 1 only)	Biased at 5 to 10mA above threshold. (AVT 0, 1 only). Ambient T (20-30°C)
B	20 (same lasers as for Test A)	4.5×10^{14}neutrons/cm^2 (mean energy = 20MeV)	5.5-7.5	Up to 400hrs	Biased at 5 to 10mA above threshold. Ambient T (20-30°C)
C	10	Not Irradiated			Biased at 60mA. Heated T=80°C
D	20	Lasers irradiated in Steps A and B			Biased at 60mA. Heated T=80°C

III. RESULTS

The L-I (light-power vs current) characteristics from 20 new lasers are shown in Fig. 3. These data are typical of all the samples measured in the three AVTs made to date: the initial laser threshold currents are around 5mA at 20°C and the output efficiencies (out of the fibre) are ~40μW/mA (±20%) as specified for the application. The threshold current is where the laser 'turns-on' and the efficiency is the slope of the L-I characteristic above this point.

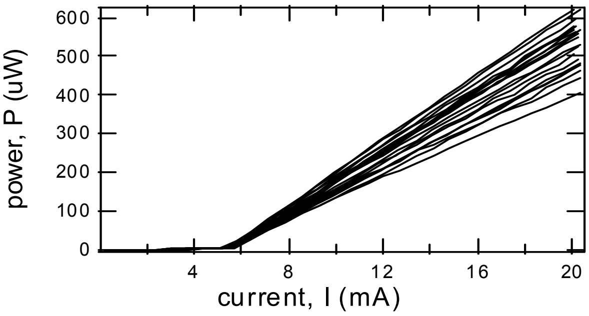

Figure 3: Typical L-I characteristics of 20 laser die packaged and supplied by ST Microelectronics (for AVT0). The light power is that measured out of the fibre.

Test A: Gamma damage.

Figure 4 shows the threshold current and output efficiency of lasers before and after 100kGy gamma irradiation, at room temperature without bias. The data are for 60 lasers from 3 different wafer lots in AVT2.

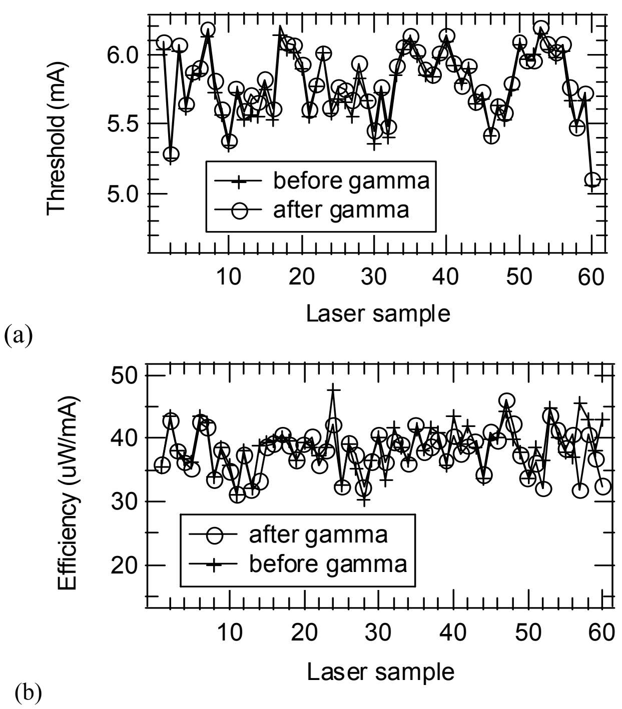

Figure 4: (a) Threshold and (b) output efficiency of sixty lasers before and after 100kGy gamma irradiation. Data from AVT 2.

Apart from small variations in efficiency, which might be partly due to the radiation-damage induced losses in the 2m long fibre pigtails, there was no other significant damage. This result is similar to that of earlier tests during qualification[6]. Also, the samples tested in AVT0 and AVT1 showed no significant damage after gamma irradiation.

Test B: Neutron damage

The properties of the lasers are much more influenced by irradiation with high energy neutrons. The threshold current increase due to neutron radiation damage is illustrated in Fig. 5, which shows measurements made before, during and after irradiation in AVT1.

Each graph in Fig. 5 corresponds to the twenty lasers from a given wafer-lot. The different times at which the damage occurred result from the devices being separated into 3 groups, with a mixture of devices from each wafer-lot per groups. The entire 60 lasers could not be placed in the neutron beam at the same time therefore only 20 lasers from the different three wafers were irradiated at a time. The mixing of the lasers from different lasers was also a precaution against possible problems with the neutron beam, which was reserved for a fixed time-period.

The neutron flux was constant during the irradiation periods. As in the earlier qualification tests[6], the threshold current increases in proportion to the neutron fluence. The threshold increase in all the lasers is in the range of 20-25mA with only a small variation across all the devices, from all of the wafer-lots.

There is a small amount of annealing during irradiation, followed by continuous annealing afterwards. During the qualification measurements[6] the annealing was observed to be proportional to $\log(t_{anneal})$. In 17 days of monitoring after irradiation in AVT 1, ~45% of the threshold damage was annealed.

The efficiency loss due to neutron damage is shown in Fig. 6, with data also from AVT 1. The data are presented with the efficiency losses normalized to the value measured just before the start of irradiation. Overall, the efficiency decreases by approximately 20%. There is a larger variation in the damage across the devices than for the threshold damage, an effect which is not understood. As with the threshold damage, 17 days of annealing after irradiation reduced the damage by ~45%.

In summary, the radiation damage effects measured during the first 3 AVTs are very similar in magnitude to those measured during the earlier qualification tests on the same type of lasers[6]. During the earlier study the damage data were extrapolated to consider a realistic 10-year operational scenario inside the CMS Tracker. In this case it was found that, because of on-going annealing, the total damage in the worst case would be limited to around 6mA threshold increase and 6% efficiency loss.

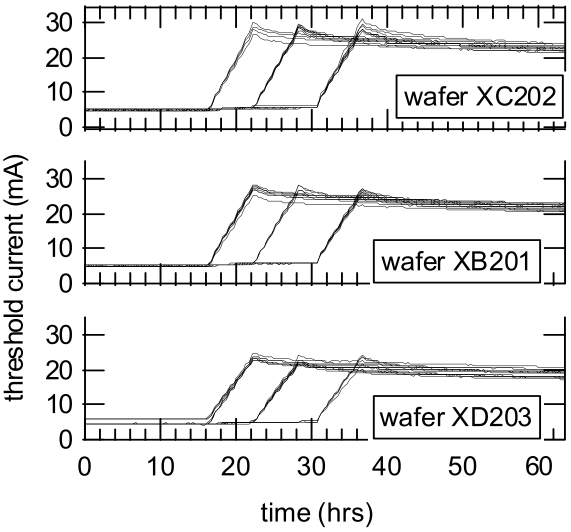

Figure 5: Threshold current measured during the neutron irradiation test to $4.5x10^{14}n/cm^2$. Data from AVT 1.

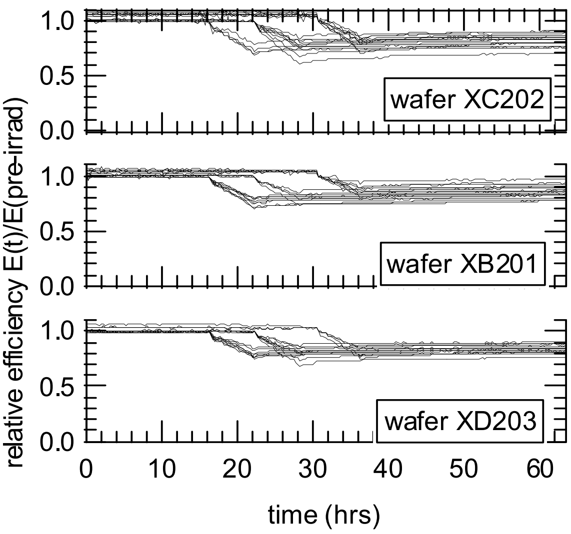

Figure 6: Normalized laser efficiency measured during the neutron irradiation test to $4.5x10^{14}n/cm^2$. Data from AVT 1.

Test C: Accelerated aging of unirradiated lasers

Wearout degradation is usually a thermally activated mechanism[7] that follows the Arrhenius law, such that the mean time to failure (MTTF) decreases with increasing temperature (hence "accelerated aging") according to,

$$\frac{MTTF(T_1)}{MTTF(T_2)} = \exp\left[\frac{E_a}{k_B}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \quad (1)$$

where $MTTF(T_1)$ and $MTTF(T_2)$ are the mean times to failure at temperatures T_1 and T_2 respectively, E_a is the activation energy and k_B is the Boltzmann constant. For this type of laser the activation energy for wearout (in unirradiated samples) has been measured as 0.73eV by Mitsubishi[8].

Fig. 7 shows data from the threshold current measurements made during aging in AVT 2, including some brief periods at 20°C. Only two lasers showed any measurable degradation, with an increase of up to 5mA after 1200 hours, measured at 80°C. This degradation was much smaller when measured at 20°C, only 0.8mA.

Similar small wearout effects were measured for AVT0 and AVT1. However, in AVT 0 all the devices had a measurable degradation and further tests are on-going at CERN to determine whether the AVT 0 wafer lot is different to a 'standard' lot. This will be done by first of all comparing the activation energy for wearout measured on AVT 0 lasers, based on accelerated aging made at different temperatures, with that measured by Mitsubishi during their internal qualification and re-qualification tests.

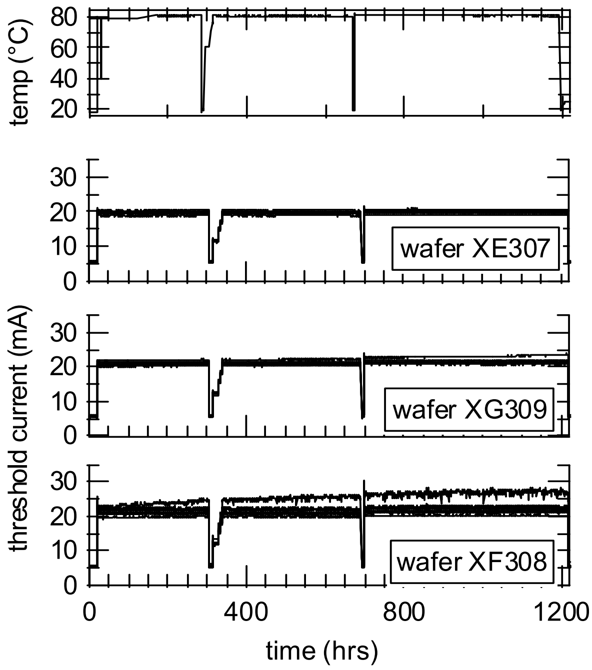

Figure 7: Threshold current measurements of unirradiated lasers during aging at 80°C. Data from AVT 2.

Assuming, for the time-being, that the same activation energy of 0.73eV can be used for the current lots of AVT lasers, ageing at 80°C for 1000 hours corresponds to $3.6x10^6$ hours at –10°C, for the operating temperature within CMS Tracker, or $1.4x10^5$ hours at 20°C, more typical of CMS ECAL.

Given these large acceleration factors and the small degradation measured at 80°C, the lasers are expected to be sufficiently reliable for use in the CMS optical link systems which have a nominal 10-year lifetime.

Test D: Accelerated aging of irradiated lasers

After the gamma and neutron irradiation the lasers are then aged at 80°C. Due to the damage after the neutron irradiation, and the exponential dependence of threshold current on temperature, the threshold current at 80°C is not measurable. Later, after enough annealing has taken place at 80°C, some lasers begin to show a measurable threshold current, but this is of little practical use in terms of determining whether wearout has taken place or not during the aging step. To compare the wearout degradation of the irradiated lasers with those in Step C, measurements are also made periodically at 20°C during the aging step.

Fig. 8 shows the threshold current of the lasers mesured during the brief periods of 20°C. The threshold values at 20°C vary little due to the influence of the aging at 80°C, except in terms of the annealing, which is concentrated in the earlier times.

In all the AVTs there is no observable (gradual) wearout in any of the irradiated lasers when the L-I measurements are made at 20°C. Only annealing is seen and it is concluded that the radiation damage does not influence the wearout characteristics significantly.

However, in AVT 1 and in AVT 2, some failures have occurred. One laser in AVT 1 and one laser in AVT 2 appeared to fail due to an open circuit. These failures have not led to disqualification of a wafer-lot, since the overall acceptance criteria allow for one failure per wafer-lot. The failed devices are now being investigated further in order to diagnose the failure mechanism more precisely.

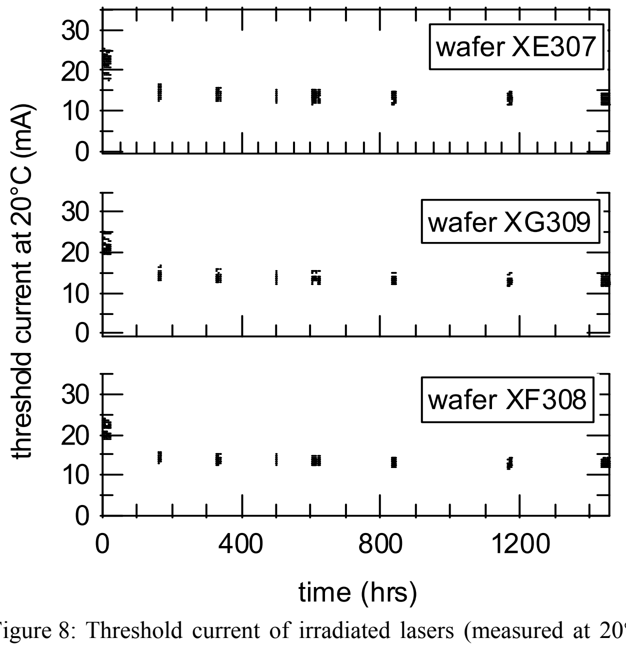

Figure 8: Threshold current of irradiated lasers (measured at 20°C) during the aging at 80°C. Data from AVT 2.

IV. SUMMARY AND CONCLUSIONS

A series of advance validation tests (AVTs), based on earlier qualification tests, are being carried out to validate lasers for final production of transmitters for the CMS optical links for readout and control of Tracker, Pixel, ECAL and Preshower subsystems.

The AVTs include radiation damage and accelerated aging measurements that attempt to determine the long-term effects of operation in the worst-case radiation environment during the first 10 years of CMS operation.

All the lasers tested in the 3 AVTs made to date have been found to be sufficiently radiation resistant for use in the CMS Tracker. The data are very similar to earlier, more detailed qualification tests, where the threshold and efficiency damage expected in the final application was estimated to be <6mA and <6% respectively.

Only 2 lasers have failed during the first three AVTs, out of 210 devices sampled from 7 wafer-lots. All the wafer-lots have therefore been accepted, from which 35000 laser die were available. The failed lasers are now under further investigation in order to establish the precise cause of failure.

Further AVTs are foreseen to complete the validation of all lasers intended for use in the CMS optical links. In parallel with this activity, further detailed analysis of the AVT data is being carried out in order to carefully compare the lasers from all the different wafers, with a view to improving our understanding of the radiation damage processes.

V. ACKNOWLEDGMENTS

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