Advance validation of radiation hardness and reliability of lasers for CMS optical links

R. Macias, M.Axer, S. Dris, K. Gill, R. Grabit, E. Noah, J. Troska and F. Vasey

***Abstract*— The production of laser transmitters for 60000 optical links is ongoing for the CMS Experiment at CERN. A series of advance validation tests (AVTs) that assure the radiation hardness and reliability has been performed on 390 edge-emitting 1310nm lasers taken from 13 different starting wafers, before the laser die have been assembled into final transmitters. The AVT also offered a first opportunity to characterize, with good statistics, the effects of radiation damage, annealing and accelerated ageing, using a large number of laser samples.**

***Index Terms*— lasers, radiation hardness assurance, reliability, CMS optical links.**

I. INTRODUCTION

Optical links, with their favourable characteristics of high bandwidth, low power, and noise immunity, will be used extensively in the new generation of High Energy Physics experiments, such as the Compact Muon Solenoid (CMS) [1], that is under construction at CERN for operation at the Large Hadron Collider (LHC) [2].

There are currently three optical link systems being constructed at CERN for CMS [3]. The first is an analogue optical link system of 43000 fibre channels for readout of the CMS Tracker, where each optical fibre carries time-multiplexed data from 256 silicon microstrips at a rate of $4x10^7$ sample/s. This development has been done in collaboration with HEPHY, Vienna and INFN, Perugia. The second system is for readout of data from the CMS Electromagnetic Calorimeter and Preshower detectors, using 11000 fibre channels and 1Gbit/s digital data transmission. This project is in collaboration with the University of Minnesota. The third system is a bi-directional 80Mbit/s digital optical link system, with 7200 fibre channels, for timing and control of the Pixel, Tracker, ECAL, Preshower and Muon-RPC sub-systems of CMS.

Radiation damage and reliability are key concerns in these systems. The operating environment in CMS is extreme by comparison with any standard telecoms or datacoms applications of optical links. It is also unprecedented in High Energy Physics experiments, as a consequence of the LHC having a much higher energy, beam intensity and collision rate compared to existing accelerator facilities. Ionizing radiation doses of up to 100kGy and particle fluences up to $2\times10^{14}/cm^2$, dominated by ~200MeV pions, are expected over the first 10 years of operation [4]. During this time, many parts embedded deep inside CMS will not be readily accessible for maintenance, repair or replacement, which raises the question of reliability. In addition to the harsh radiation environment, there is also a strong magnetic field (4T) and parts of the optical links, for example in the Tracker, will be operated cold, at –10°C to mitigate the effects of radiation damage in the silicon microstrip detectors [4]. These additional factors are expected to be less demanding [5], [6] than the radiation damage and reliability.

Despite the highly specialized and harsh operating environment, budgetary constraints have meant that the optical link systems have to be built from commercial off-the-shelf (COTS) parts wherever possible, to reduce the development and qualification costs. In addition, the optical link developments for CMS were also largely consolidated such that the smaller digital link systems mentioned so far are based upon on the much larger analogue optical link system, which was already well advanced when the digital links projects were still being developed. Multiple developments or procurements of similar objects have therefore been avoided and a unique series of quality assurance tests has been made on the shared parts, namely the lasers and several types of optical fibre cables and connectors. This testing included qualification and assurance of radiation hardness and reliability [7] and in this paper we will focus on the laser testing.

Altogether, more than 65000 lasers in total will be required for the three optical link systems (plus spares). The laser die selected is the Mitsubishi ML7CP8 1310nm multi-quantum-well InGaAsP/InP edge-emitter. The lasers are supplied to CMS by STMicroelectronics (STM) in a semi-custom package [3], which consists of the laser die attached to a silicon optical sub-mount and fibre-pigtail, with the submount having a simple lid-cover, rather than being housed in the standard STM mini-DIL package. This bare assembly minimizes the size and mass of the transmitter overall, reducing its contribution to the material budget [4] of the CMS Tracker, where additional dead material will degrade both the performance of the Tracker and the ECAL detector systems. In addition, to avoid additional potential radiation effects, there are no lenses used in the package between laser and fibre. The laser is protected by means of a silicon lid that is

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glued with a small amount of epoxy to the optical sub-mount. The device is not hermetically sealed, the package contains no encapsulation or potting compound, and when mounted on a CMS optohybrid there is no additional encapsulation applied. The optical fibre used in the pigtail is standard Corning SMF28 single-mode fibre, jacketed with an acryllate buffer by Ericsson Cables. The fibre pigtail is terminated with an MU connector supplied by Sumitomo. The optical fibres and connectors have been qualified previously to be sufficiently radiation-resistant for the CMS application and the radiation effects are small and do not significantly affect the data presented in this paper.

The laser transmitter in its final packaged form was qualified for final production in 2002. The qualification included radiation hardness and reliability tests on 28 samples, to the equivalent of the worst-case levels of radiation exposure expected inside CMS, as well as for wearout well beyond a period of 10 years [8]. There were no failures in this test and the radiation damage was expected to be limited, in the worst case exposure within the CMS Tracker, to a 5mA threshold shift and 5% efficiency loss after 10 years of irradiation (and concurrent annealing). No wearout was observed in parts that had been irradiated that were subsequently aged at 80ºC for 2500 hours.

Despite having been qualified, the radiation hardness (and reliability) assurance tests have been continued into the final production stage of the project. These are the ‘advance validation tests’ (AVTs) detailed in the following Section, where a small number of laser samples are taken from a given starting wafer, intended for final production, that are then checked for radiation hardness and reliability before the wafer is released for final production.

The AVTs were considered to be essential since the Mitsubishi laser die, and the basic parts of the package made by STM are COTS components, and their uniformity of response to radiation, is not guaranteed. The mechanisms of the radiation damage, considered very briefly below, are also not well enough understood to be confident of the radiation hardness of the final parts without making further tests. Finally, taking into account the large value added in packaging the lasers, it was in any case considered reasonable to check the reliability of each wafer, regardless of the radiation hardness, before making a full batch of final transmitters.

As well as providing assurance of the radiation hardness and reliability of the final laser transmitters, the series of AVTs has also provided a unique opportunity to study the radiation hardness and reliability of a large number of laser diodes from a single manufacturer, under well defined conditions and a large amount of data has been collected that will be presented here in a condensed form.

The known and readily observable effects of radiation damage and wearout in lasers share some similarities. Both radiation damage [8]-[11] and wearout [12]-[13] are often manifested as an increase in the laser threshold current, accompanied by a decrease of the laser efficiency. These effects result from the accumulation of defects in and around the active volume of the laser, which create new energy levels in the semiconductor band-gap that can act as non-radiative recombination centres [14].

The detailed kinetics of the degradation and the long-term behaviour of the defects introduced by radiation damage or wearout are however very different. Irradiation introduces defects throughout the laser structure through displacement. The threshold increase and efficiency loss are observed to be proportional to the fluence[8]. Ionization damage, as will be shown later, is not significant in lasers at least for levels of up to 100kGy (unless there are dose-sensitive parts in the packaging [15]).

In contrast, wearout degradation in InGaAsP/InP is most often related to defects introduced during processing of the device [13]. Wearout is a thermally activated mechanism [12], [16], following the Arrhenius law and the average (median) time to failure (t_m) decreases with increasing temperature following

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

where $t_m(T_1)$ and $t_m(T_2)$ are the mean times to failure at temperatures T_1 and T_2 respectively, E_a is the activation energy (typically between 0.4eV and 0.7eV [17]-[19]) and k_B is the Boltzmann constant.

The effects of radiation damage have the opposite tendency to those of wearout under conditions of increased time or temperature. The initial displacement damage is not thermally influenced, since the energies involved in atomic displacements are well in excess of the thermal energy of the atoms. Annealing of the radiation damage is however thermally activated [8]. The thermal motion of the atoms results in some reordering of the crystal and recovery from the radiation damage. In 1310nm MQW lasers we have found that the annealing is proportional to log(anneal-time) which is consistent with a uniform distribution of activation energies [20], [21] for annealing of the radiation induced defects.

In the following Section we will describe how the radiation damage and wearout have been measured during the AVTs. All of the effects of radiation damage and wearout in lasers that were described above are clearly apparent in the results. In addition, the large amount of data collected allows a detailed comparison of damage and wearout between nominally identical lasers from many different wafers.

II. Advance validation test (AVT) Procedure

The AVT procedure is an integral part of a wider quality assurance (QA) programme for the optical links project [22]. The AVT was defined based on the procedures that were used successfully during the earlier prototype validation and subsequent qualification tests [8], [23], [24]. The procedure is illustrated in Fig. 1.

Table 1: Experimental conditions for the radiation damage and accelerated ageing studies in the AVTs

Test step (see Fig. 1)	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 (Irradiation)	20	100kGy (^{60}Co-)	48 (SCK)	12 (AVTs 0, 1)	Biased at 5 to 10mA above threshold. (AVT 0, 1). Ambient T (20-30 C)
			~150 (at UCL and Ionisos)	None (AVTs 2, 3, 4)	Unbiased, lasers shorted. (AVT 2, 3, 4) Ambient T (20-30 C)
B (Irradiation)	20 (same parts as Test A)	5x10^{14}neutrons/cm^{2} (<E> = 20MeV)	6.0-7.5	Up to 400hrs	Biased at 5 to 10mA above threshold. Ambient T (20-30 C)
C (Ageing)	10	Not Irradiated			Biased at 60mA. Heated T=80 C
D (Ageing)	20	Lasers irradiated in Steps A and B			Biased at 60mA. Heated T=80 C

Sample groups of 30 devices were chosen randomly from each wafer, packaged in their final form and burned-in by STM. The AVT procedure was then divided into several stages (Steps A to D) as summarized in Table 1. Steps A and B are measurements of damage and annealing with gamma and then neutron sources respectively (20 devices). Steps C and D involve accelerated aging (all 30 devices). If the AVT was passed then the remainder of the die from the corresponding wafer was accepted for the production of laser transmitters for CMS by STM.

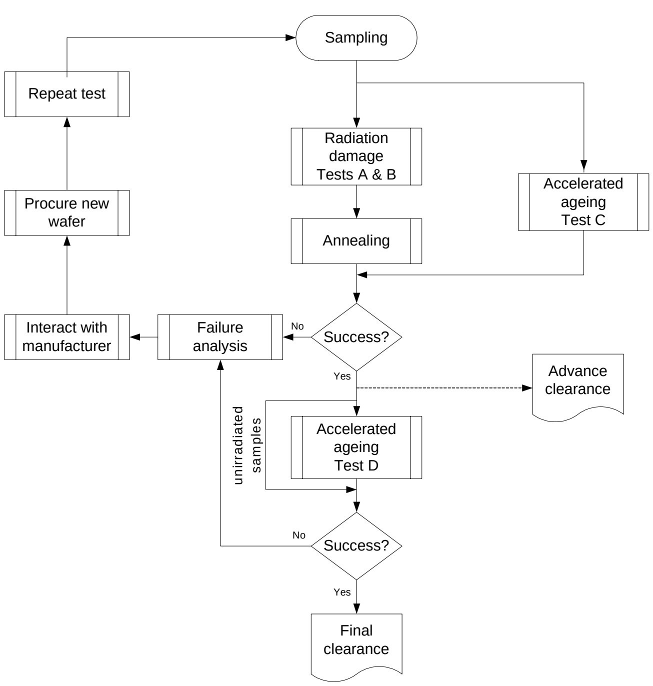


Fig. 1. Flow chart of the laser AVT procedure. Conditions for tests A-D are given in Table 1.

Five AVTs have taken place to date and these have validated enough laser die (at least 3000 per wafer, from 13 wafers) to be able produce 60000 fully assembled transmitters for the CMS optical links. At least one further AVT will be made to validate extra components intended for spare parts.

The irradiation steps were made at room temperature with devices usually under electrical bias. Lasers were irradiated with ^{60}Co gamma rays and then 20MeV (average energy) neutrons, up to doses and fluences equivalent to the worst-case in the Tracker, i.e. 100kGy and 5x10^{14}(~20MeV neutrons)/cm^{2}.

In the case of the gamma tests, no damage was found to occur during qualification, or during the first two AVTs, as will be shown in the results. In the subsequent AVTs, gamma irradiation was then simplified and made in a passive manner, with the lasers irradiated at room temperature, still with ^{60}Co gamma to 100kGy, but without electrical bias or in-situ measurements. In these tests, measurements were made instead before and after the irradiation, to check for any damage. ^{60}Co-gamma facilities included the RITA facility of the SCK-CEN [25] laboratory in Mol, Belgium for tests with in-situ monitoring. The Ionisos [26] ^{60}Co facility in Dagneux, France and a ^{60}Co source at the Cyclotron Research Centre (CRC) [27] at Louvain-La-Neuve, Belgium were used for passive tests. In all cases the target dose was 100kGy and polyalanine (PAD) dosimeters were used to measure the actual doses with an accuracy of approximately ±10%. Up to 60 samples were irradiated simultaneously and the dose was uniform across the samples and stable over the irradiation period, which was typically several days long.

Neutron irradiation was made using the T2 facility at CRC [27]. An intense and approximately constant flux of neutrons is available with an average energy of ~20MeV, from a beryllium target bombarded with 50 MeV deuterons. The lasers were irradiated in stacks of 20 devices, with up to 3 stacks, i.e. 60 lasers were irradiated consecutively during each AVT. Dosimetry of the neutron irradiation was made based on a measurement of the integrated beam current combined with previous calibration of the neutron flux [27].

In-situ monitoring of the laser characteristics was made using measurements of the laser L-I (light-power vs. current) and V-I (voltage vs. current) at periodic intervals, during and after irradiation. Identical test and measurement procedures were used during the AVT as those used during the earlier device qualification[8], this consistent approach enabling a stable comparison of data between different laser wafers and between different irradiation tests.

During the accelerated ageing (Steps C and D) the devices were operated at 80°C and 60mA for at least 1000 hours to measure any potential wearout degradation. Ageing at 80°C for 1000 hours corresponds to 3.6×10^6 hours at –10°C, for the operating temperature within CMS Tracker, or 1.4×10^5 hours at 20°C, more typical of CMS ECAL, based on the activation energy of 0.7eV [19]. Again, in-situ monitoring of the laser L-I (light-power versus current) and V-I (voltage versus current) characteristics was done with measurements made at periodic intervals during the ageing tests. Measurements were made at 20°C at ~200 hour intervals during ageing so that we had a direct comparison with data from before the ageing. These measurements were used to estimate the time-to-failure as outlined below. The lower measurement temperature was also necessary to monitor the wearout of the irradiated lasers, which did not all lase at 80°C after neutron irradiation because of the strong temperature dependence of the non-radiative mechanisms.

Finally, the acceptance criteria for the wafers being validated in the AVTs were defined by considering the effect on the overall optical link performance due to degradation of the laser. The criteria are applied after taking into account the effect of the worst-case radiation damage exposure (and annealing), and wearout degradation, after extrapolating to the full 10-year lifetime of the links. This extrapolation is described in detail in the qualification report [8].

The two failure modes related to wearout, that are considered to be most probable and therefore most important, are illustrated in by the sketches of laser light-current (L-I) characteristics shown in Fig. 2. The lifetime of the lasers has been calculated in terms of both of these failure modes in the analysis of the ageing data.

For an individual laser to pass the AVT the combined effects of radiation damage (and annealing) and ageing are not allowed to increase the threshold current beyond the maximum dc current supply of the LLD [28] laser driver ASIC, which is 45mA (in the worst case). Since most links will operate in the CMS Tracker at –10ºC then it can be shown that the 45mA limit at this temperature corresponds to a maximum change of 55mA in the threshold current measured at 20ºC, after taking into account the contribution of radiation damage and the starting threshold current.

The other failure mode related to wearout is that due to a decrease in laser efficiency. This second type of failure has only been defined more recently, when it was realised that this type of failure was, in fact, more likely to occur than a failure due to the threshold increase. The failure level is defined as being when the output efficiency of the laser has fallen below 50% with respect to the initial value. This is a 'soft' failure mode in comparison to the laser threshold failure, since the loss of efficiency, so long that it is gradual, is unlikely to kill an optical link outright. It is only likely to degrade the optical link performance in terms of signal to noise, (or bit-error-rate), which might still remain tolerable when considered in the wider context of the final performance of the Tracker or some other detector system in CMS where the links are used.

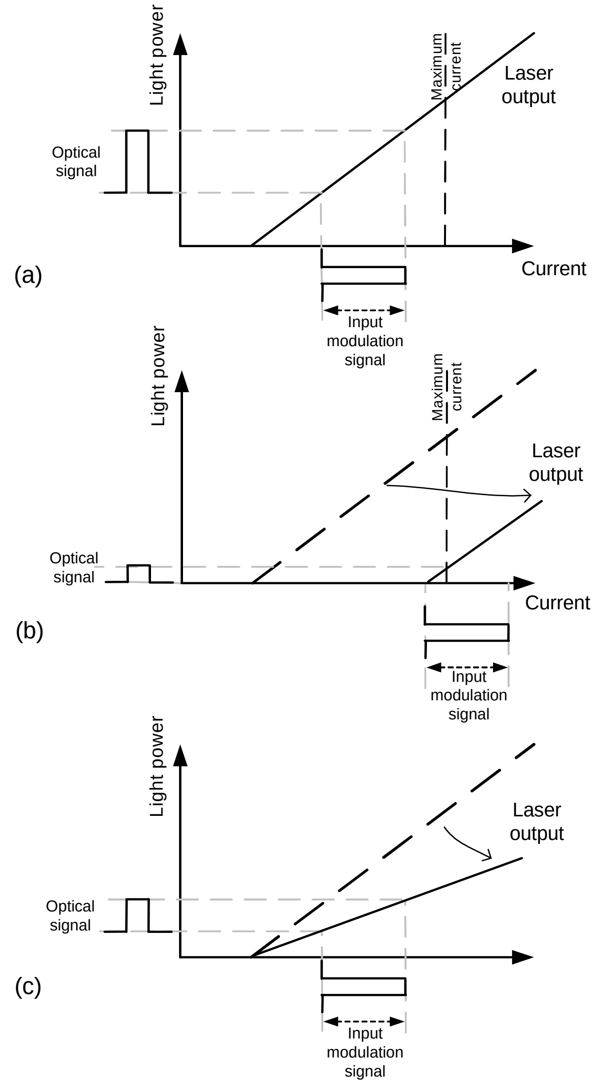


Fig. 2: Schematic laser light-current (L-I) characteristics to illustrate the two main failure modes considered in the AVT. (a) Normal, working laser. (b) Failure due to the laser threshold increasing beyond the maximum dc supply of the laser driver ASIC, and (c) due to 50% loss of initial output efficiency.

The above criteria cover the individual lasers, but to accept or reject the entire wafer being validated an overall level of acceptable failure has to be defined. This was chosen to be 5%. During the AVT we did not expect any devices to fail due to radiation damage. Similarly, we did not expect any failure due to wearout, as the lifetime of these lasers is reported by the manufacturer [19] to be far in excess of 10 years when operating at or below room temperature. However, we decided that we should allow for the possibility of an unpredictable, or random failure of a part during the AVT. The 5% limit effectively therefore allows one device out of 30 samples in a given wafer, to fail for a reason other than wearout, without requiring us to reject the whole wafer unnecessarily.

Up to this point we have deliberately restricted the discussion of reliability to radiation damage and wearout degradation.

We acknowledge that there are many other possible types of failure mode[12], [13] in lasers. In particular, those related to random mechanisms can also be very important in determining device failure rates, particularly in devices that show little wearout such as the lasers under test here. However, a measurement of the random failure rate was far beyond the scope of the AVT since it can only be done in a meaningful way by analysing actual field-data from a significant number of devices.

III. AVT RESULTS

The L-I characteristics from 20 unirradiated lasers are shown in Fig. 3. The threshold current is where the laser 'turns-on' and the efficiency is the slope of the L-I characteristic above this point. To determine these values we fit a line to the first few data points (typically at 1mA steps) of the L-I characteristic starting where the output power passes 25µW. The threshold is the intercept of the fitted line with the current-axis and the efficiency is the slope of this line. The 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 uncertainty in the measurements is very small compared to the size of the effects being measured. The reproducibility, under stable measurement conditions, of the threshold current measurement is 0.01mA (rms) and for the efficiency measurement 0.3% (rms). Apart from noise effects the efficiency measurement may also be affected by variations in the connector insertion loss if the fibre has been disconnected and reconnected, e.g. before and after gamma irradiation. In this case the insertion loss of the MU connector may be up to 0.5dB, though it is typically less than 0.2dB.

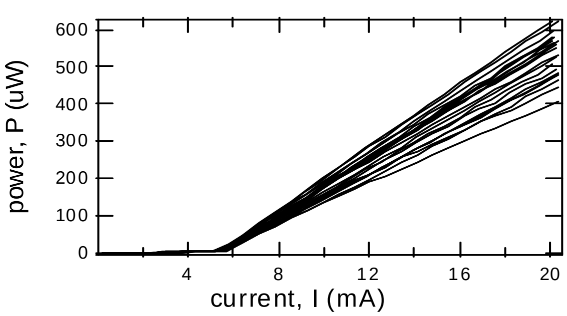


Fig. 3. Typical L-I characteristics of 20 laser die packaged and supplied by ST Microelectronics (for AVT0). The light power is that measured out of the fibre.

A. Gamma irradiation (AVT Test step A)

Figure 4 shows an example of the threshold currents and efficiencies measured in a group of 60 lasers from 3 wafers (in AVT 3) before and after 100kGy gamma irradiation. There was no significant damage due to gamma irradiation to this dose, as was the case in all the other AVTs as well as earlier measurements during qualification.

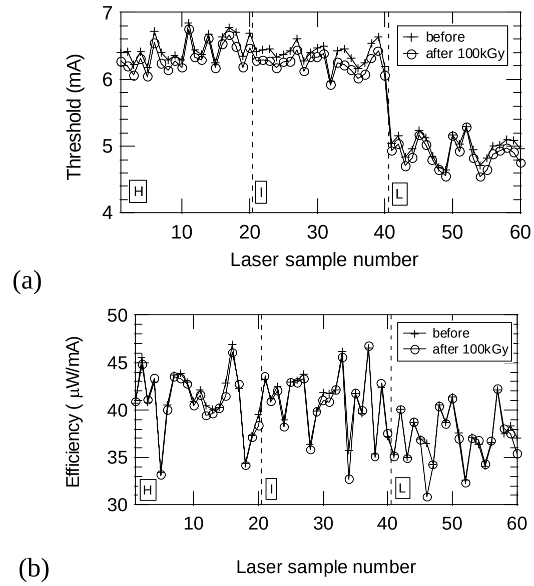


Fig. 4. (a) Threshold currents and (b) efficiency measured in sixty lasers from 3 wafers before and after 100kGy gamma irradiation. Data from AVT 3.

B. Neutron irradiation (AVT Test step B)

1) Radiation Damage

The properties of the lasers were much more influenced by irradiation with high-energy neutrons, as illustrated in Fig. 5, which shows the typical changes in the L-I characteristic for one of the lasers tested. Fig. 6 shows how the threshold and efficiency (normalised to the initial efficiency) in a group of 20 lasers from one wafer changed during neutron irradiation.

These data are representative of the results from all the AVTs.

As in the earlier qualification tests[8], and as with measurements on many other similar lasers [23], the radiation damage in terms of either threshold current increase, or efficiency loss, was proportional to the neutron fluence.

Since the test conditions were very similar in each AVT, and since the damage is clearly proportional to neutron fluence, a direct and simple comparison of radiation damage in devices within a given wafer and between different wafers can now be made. The data was first normalized to represent the damage expected after a fluence of $5x10^{14}$n/cm^2 in 6 hours of irradiation at CRC, using the data taken for each laser during the first 6 hours of irradiation. The full statistics from the different wafers are given in Fig. 7, for the threshold increase and efficiency loss.

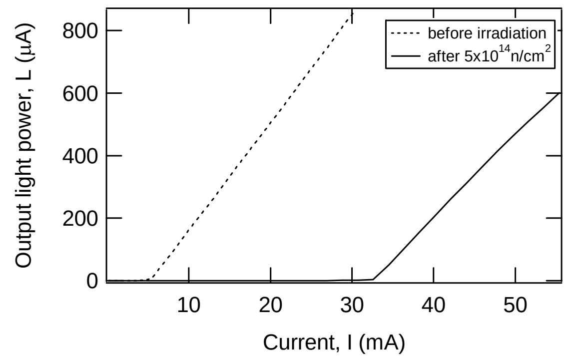


Fig. 5. Typical changes in laser L-I characteristic, threshold increase and efficiency loss, caused by neutron damage from a fluence of 5×10^{14}n/cm^2 (~20MeV) accumulated over 7 hours at 20°C.

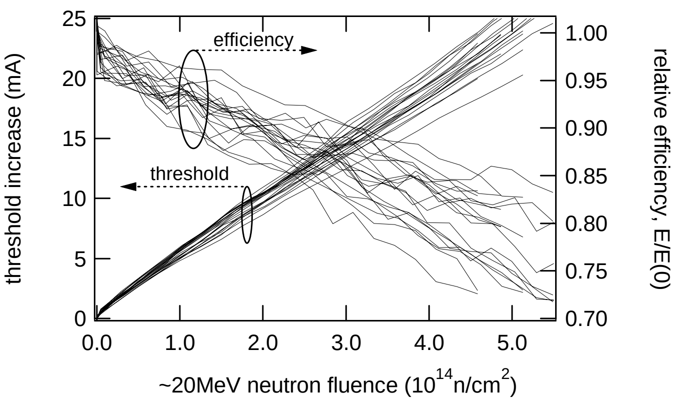
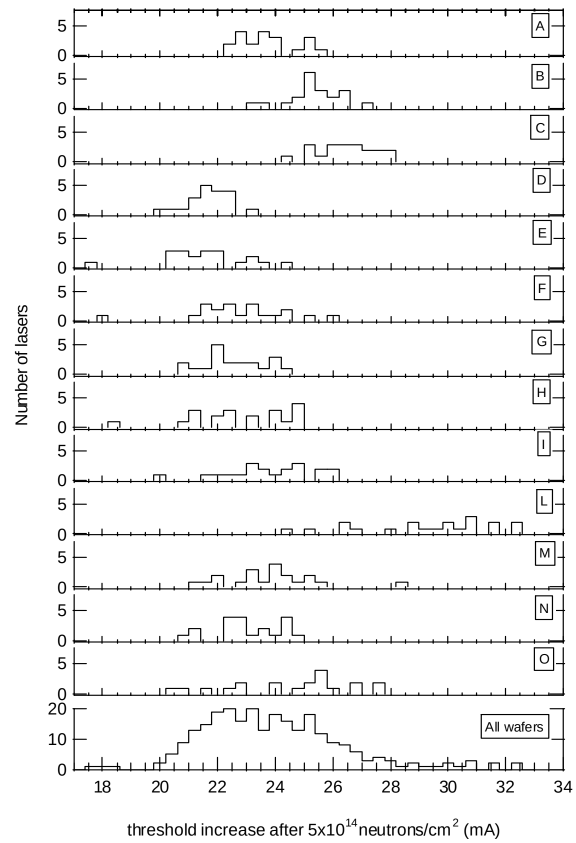


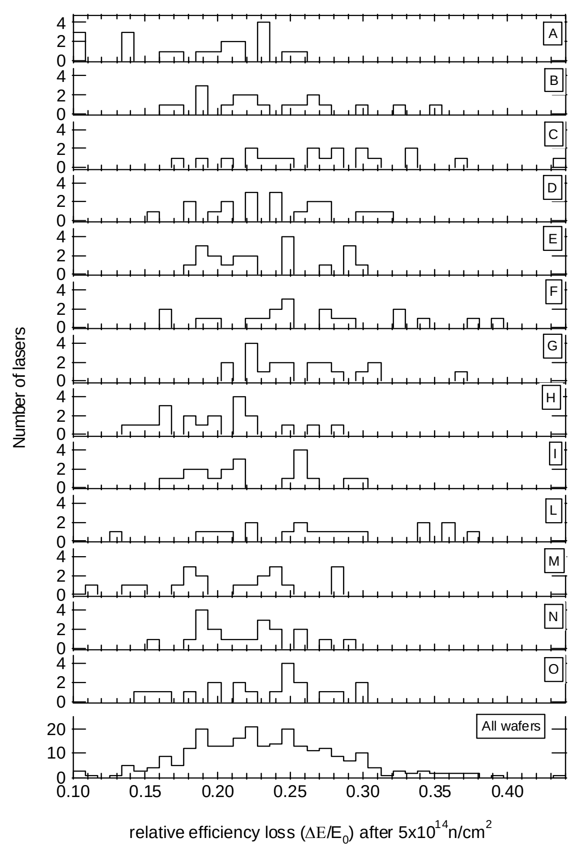
Fig. 6. Example of threshold current change and normalized efficiency change. Data for 20 lasers from wafers I, irradiated with neutrons in AVT3.

The threshold increase in all the lasers was on average 24mA, with most devices having a shift between 20 and 28mA. There was a relatively small variation across samples from a given wafer (typically ±15%) but larger differences from wafer-to-wafer. Normalizing the damage relative to the initial threshold current i.e. $I_{thr}/I_{thr}(0)$, which is the usual method of analysing threshold damage [9]-[11], made the distribution within each wafer slightly narrower, but the differences between the wafers were then even greater. For example, wafer L had the greatest damage overall but the initial thresholds were amongst the smallest, close to 4mA, so the normalised damage could be up to twice that observed in other wafers. This normalisation was therefore not appropriate for comparing the damage in these particular lasers since the initial threshold current did not govern the sensitivity to radiation damage.

For the efficiency damage, the average loss was 23%, distributed mainly between 14% and 31% loss. The range of damage was already broad within a given wafer, compared to the threshold damage, though the range of efficiency loss was more similar from wafer to wafer than the threshold damage. Unfortunately, the efficiency data had to be normalized already with respect to the initial value to account for the different laser-to-fibre coupling efficiencies achieved when packaging the lasers. This means that, unlike the threshold results, we were not able to measure whether the initial laser output efficiency affected the amount of radiation damage.



(a)



(b)

Fig. 7. Comparison of the radiation damage across all 13 wafers tested, during AVTs 1-5 in terms of (a) threshold damage and (b) efficiency loss. The results are based on a normalization to a total fluence of 5×10^{14}n/cm^2 (~20MeV) accumulated over 6 hours at 20°C.

2) Annealing

The annealing of the damage after neutron irradiation is illustrated in Fig. 8 for both the threshold current and efficiency in the irradiated lasers from one wafer. The data is also very similar for the other wafers. The annealing is plotted in terms of the remaining fraction of the damage measured at the end of the irradiation.

The annealing was observed to be proportional to log(anneal-time), as in earlier studies [21], from a point starting a few hours after irradiation for both threshold and efficiency damage. This type of annealing is consistent with there being a range of activation energies for annealing [20], [21].

Both the threshold and efficiency damage anneal at the same rate, confirming that these radiation damage effects are caused by the same set of defects. The slow start to the annealing reflects only the fact that the annealing expected at short times on this plot has occurred already during the irradiation.

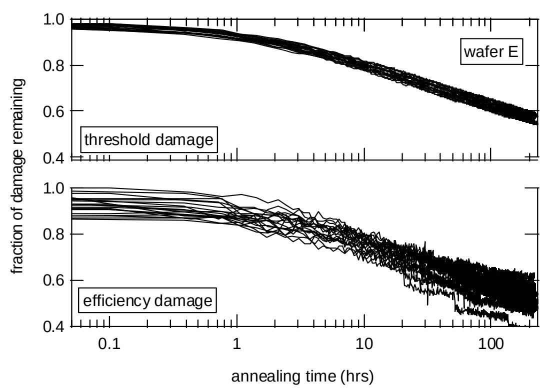


Fig. 8. Annealing of the threshold current and efficiency damage after neutron irradiation for 20 lasers from one of the wafers tested.

The overall amount of annealing is very significant, especially considering the 10-year lifetime of the lasers inside CMS. The annealing observed in the AVTs is very similar to that measured during qualification of these lasers [8], when it was demonstrated, using thermal acceleration, that the same trend of annealing continues at least until 70% of the damage has recovered.

In summary of this step of the AVT, all the devices pass the test and the results match closely with those in the earlier qualification studies [8]. In the earlier studies a full extrapolation of the radiation damage and annealing over the CMS lifetime was made. The worst-case damage from $2x10^{14}$pions/cm^2 (E_π~200MeV) at the centre of the CMS Tracker was expected to be limited to 6mA threshold increase and 5% efficiency loss. The lasers tested in these AVTs should, on average, have a similar level of damage in the worst-case.

C. Ageing of unirradiated lasers (Test step C)

In all but two wafers (A and M) there was very little degradation observed in any of the lasers. Fig. 9 shows an example of ageing data (60mA, 80°C) for unirradiated lasers from wafers M, N and O in AVT 4. The measurements plotted were made periodically at 20°C to assess the wearout with respect to the initial properties of the device.

Wafers N and O are similar to most of the other wafers that have been studies, in that they show little wearout in terms of increased leakage current or decrease in efficiency. In contrast there is a clear increase in threshold current and loss of efficiency in devices from wafer M. This wafer was similar to one other that was tested, wafer A.

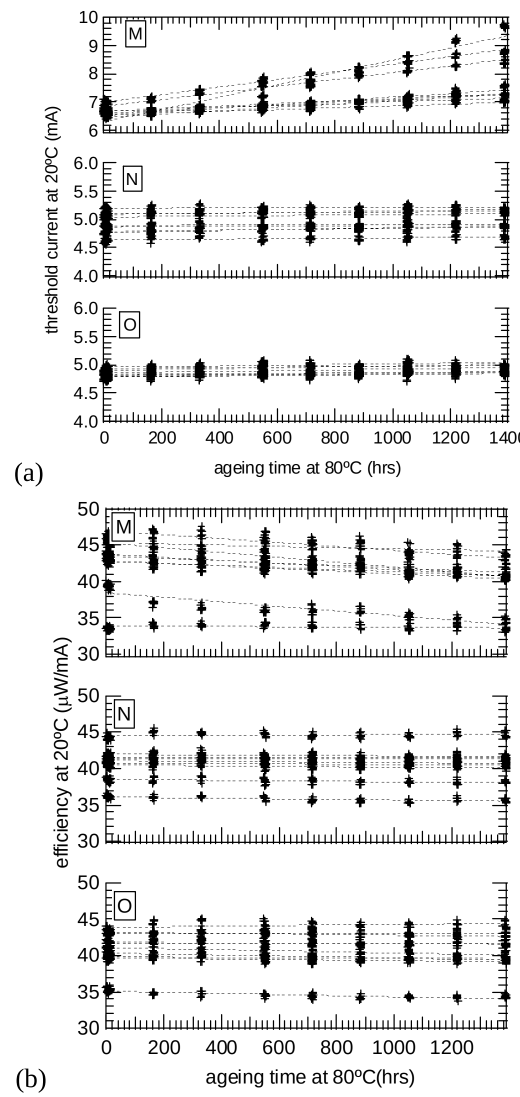
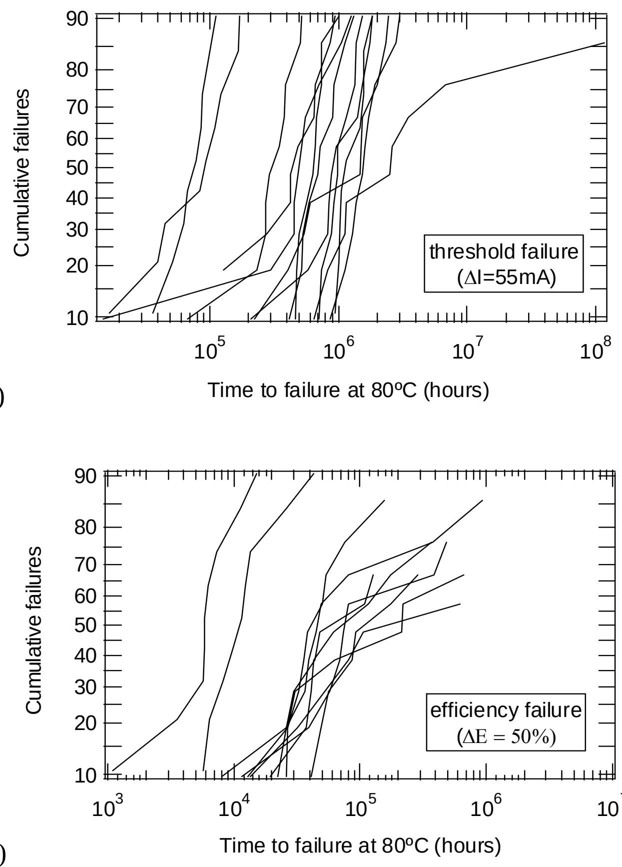


Fig. 9. (a) Threshold current and (b) efficiency degradation of unirradiated lasers from wafers M, N and O during aging at 80°C in AVT4. Lines have been fitted to the data to illustrate the rates of wearout.

The degradation appeared to be linear with ageing time therefore the time-to-failure was estimated for each laser by extrapolating [29] the ageing data to the failure criteria outlined earlier in Fig. 2, these were ΔI_{thr} = 55mA (current measured at 20°C) and ΔE=50% (at 20°C). A summary of the statistics for both failure modes is plotted in Fig. 10 for all the wafers.

The data have been plotted on a log-normal chart. Most data points from each wafer lie on a straight line, confirming that the wearout follows a log-normal distribution [30]. This distribution often describes wearout degradation in semiconductor devices [12].

There were some wafers where several samples were not degrading measurably (particularly for the efficiency loss) during the ageing test and their time-to-failure was not possible to estimate. However, in all cases the lifetime of more than 50% of the devices could be estimated and the median life t_m and standard deviation σ could therefore be estimated, t_m is when the cumulative failures reach 50%, and σ is $\ln(t_m/t_1)$ where t_1 is where the cumulative failures reach 15.9%. Excluding wafers A and M for the time-being, $t_m \sim 10^6$ hours at 80°C in terms of the threshold increase (with $\sigma \sim 0.5$) and $t_m \sim 10^5$ hours at 80°C in terms of the efficiency loss (with $\sigma \sim 1.5$).



(a) (b)

Fig. 10. Summary of estimated time to failure based on linear fit and extrapolation of 80°C ageing data from unirradiated lasers from all wafers, related to (a) threshold current increase and (b) efficiency loss.

The average lifetime t_m for devices operating under CMS conditions can therefore be estimated, using equation (1). In the CMS Tracker, at -10°C, t_m for lasers from all the wafers (except for A and M) would be in excess of 10^{10}hrs considering the threshold increase, and 10^7 hrs for the efficiency loss [31]. In the CMS ECAL, at a temperature of 20°C, t_m is expected to be around 10^8hrs regarding the threshold increase, and 10^6 hrs for the efficiency loss.

These are very long lifetimes compared to the 10-year operational lifetime and the failure rate λ is instead a more useful figure to consider. Considering the efficiency loss failure mode, since it is most likely to occur, the lognormal distribution has $\sigma \sim 1.5$ and the failure rate will increase over the lifetime of CMS [30]. After 10 years of operation, λ=20FITs for lasers in the Tracker and λ=1000FITs in the ECAL, where 1 FIT is a standard unit of failure rate of 1 device per 10^9 device hours [16, 30].

Summarizing the ageing of the unirradiated lasers, all the wafers passed this part of the AVT as expected and very few lasers are expected to fail due to wearout during operation inside CMS. Other failure mechanisms such as those related to random causes are expected instead to dominate the overall failure rate, but this statement cannot yet be quantified without field-data. Concerning the wafers A and M, we had some reservations regarding the use of these wafers in the final CMS optical links, due to the much smaller device lifetimes of samples taken from these wafers. As a consequence, most of the lasers produced from wafer A, which were assembled before it was realised that this wafer was much less reliable than most of the others, have only been used for preproduction test-systems in CMS. For wafer M, we are in discussion with the manufacturers to find a replacement for this wafer.

D.Ageing of irradiated lasers (Test step D)

After the gamma and neutron irradiation the lasers were then also aged at 80°C. As with the unirradiated parts, the irradiated devices were measured at 20°C at periodic intervals, typically 150-200 hrs. Some typical results are shown for the threshold currents in Fig. 11, with data from AVT 3.

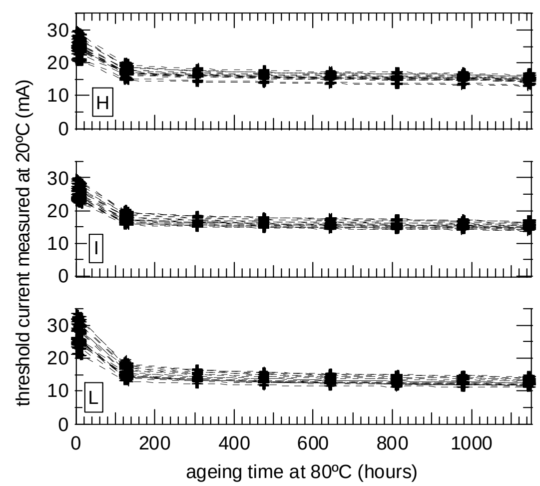


Fig. 11. Threshold current in 30 irradiated lasers (wafers H, I and L), measured at 20°C at periodic intervals during aging at 80°C.

The threshold current at 20°C varies little due to the influence of the aging at 80°C, and only the effects of annealing are visible, particularly near the beginning of the ageing. The same comments also apply to the efficiency measurements. The annealing may well have masked wearout effects so we have concluded that a precise measurement of wearout was not possible, however since it is expected that the annealing rate is relatively slow towards the end of the ageing test, any significant wearout, such as that observed in unirradiated parts from wafers A and M would still have been visible.

The data shown in Fig. 11 are representative of all the wafers tested, and the observation of little wearout is also consistent with the conclusions of other ageing studies that we have made on neutron irradiated devices from different manufacturers [24], [32].

IV. CONCLUSION

CMS optical links require the manufacture of more than 60000 laser transmitters. The devices must be radiation hard and reliable enough to work for 10 years in an extreme radiation environment.

The lasers are based on COTS components, therefore we have established an advance validation test (AVT) procedure to check the radiation hardness and reliability of wafers before mass production takes place. The test procedures are based on those already put in place during earlier stages of the project.

5 AVTs have been performed to date on devices from 13 wafers, with at least 3000 samples validated per wafer. At least one more AVT is required to cover the final quantity of transmitters, but already there are enough statistics to draw some final conclusions.

In terms of radiation damage, the threshold increased by an average of 24mA and the efficiency decreased by an average of 23% after $5x10^{14}n/cm^2$ (~20MeV neutrons). The damage in each wafer was similar, but from wafer to wafer there were some greater differences. Gamma irradiation caused no significant damage.

Annealing of the neutron damage is significant over long timescales and much of the observed damage is unlikely to be present over longer irradiation periods, such as during the 10 year lifetime of the devices in CMS.

The reliability of the devices is very good in general with device MTTF well in excess of the 10-year operational lifetime. Two wafers exhibited much greater degradation than the other wafers and we will try to avoid using lasers from these two wafers in the final optical links.

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