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Ageing Tests of Radiation Damaged Lasers and Photodiodes for the CMS Tracker Optical Links

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Abstract

The effects of thermally accelerated ageing in irradiated and unirradiated 1310nm InGaAsP edge-emitting lasers and InGaAs p-i-n photodiodes are presented. 40 lasers (20 irradiated) and 30 photodiodes (19 irradiated) were aged for 4000 hours at 80°C. Periodic measurements were made of laser threshold and efficiency, and p-i-n leakage current and photocurrent.

There were no sudden failures and there was very little wearout related degradation in either unirradiated or irradiated sample groups. The results suggest that the tested devices have a sufficiently long lifetime to operate for at least 10 years inside the CMS Tracker despite being exposed to a harsh radiation environment.

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1. Introduction

1.1 Optoelectronics in the CMS Tracker

A system of 50000 analogue and several thousand digital optical links is being developed at CERN for readout and control of the CMS Tracker[1,2]. The optoelectronic devices inside the tracker will be exposed to a harsh radiation environment over the lifetime of at least 10 years. The maximum radiation fluence will be ~$2x10^{14}$particles/cm^2 (at 20cm radius from the interaction point) composed mainly of pions (>100MeV) and neutrons (~1MeV), in addition to an ionizing dose of ~100kGy[2]. All of the optical link components being considered for use inside the tracker therefore have to be qualified for both sufficient radiation hardness and reliability.

The optical links will be based on 1310nm InGaAsP edge-emitting lasers and InGaAs p-i-n photodiodes, coupled via standard telecom single-mode fiber with several connectorized break-points[1]. The analogue links will run at 40Msample/s and the digital links will run at 40MHz. Manufacturer-qualified commercial off-the-shelf (COTS) components will be used as much as possible in the optical link system, as these components are already known to be highly reliable. However, it was not known whether radiation damage influences the reliability of optoelectronic components. In our previous studies, we have confirmed the radiation resistance, in terms of device performance, of InGaAsP lasers and InGaAs photodiodes from many manufacturers up to the CMS tracker fluence and dose levels[3,4]. In this paper we investigate the influence of radiation damage on the ageing behavior of 1310nm InGaAsP lasers and InGaAs p-i-n photodiodes.

1.2 Reliability of lasers and photodiodes

Component reliability is often categorized into three domains: early, mid-life, and old-age failure, each with several different mechanisms[5,6] that contribute to the failure rate.

Early failures that occur in lasers and p-i-n photodiodes (sometimes termed ‘infant mortality’[5]) are usually intrinsic to the device. Production problems, such as poor epitaxial growth, or faults during mounting or packaging (bad gluing, faulty wire-bonding or soldering, or inclusion of particles or moisture) can all be causes of failure during early life. Fortunately most of these failure modes can be eliminated by a burn-in, or purge-test, inducing weak devices to fail before the components are employed in the field.

The mid-life failures can be subdivided into two parts, the first being simply due to the tails of the early and long-term failure distributions. The remaining failures are collectively grouped together as ‘sudden’ or ‘random’ failures, which are catastrophic failures often triggered by external factors such as electrical or mechanical shocks, depending upon the operating environment.

Long-term failures are usually dominated by intrinsic ‘wearout’. In semiconductor lasers this degradation is often manifested by the growth of dark-spot or dark-line defects (DSD and DLD)[6,7], though these defects rarely form in InGaAsP lasers, unless introduced during fabrication[7]. Another wearout mechanism in buried heterostructure lasers is the build-up of trapping/recombination centers in the p-n junctions of the confinement structures that degrades the effectiveness in limiting the flow of injected current to the active volume of the laser[6]. The practical effect of these mechanisms is that the laser threshold current increases and the output efficiency may also decrease[6]. In p-i-n photodiodes, defects that act as generation-recombination centers can build-up over time around the sensitive layer, usually causing an increase in the leakage current[8,9].

For the optical link components inside the CMS tracker the lasers are considered to be the most sensitive elements in terms of reliability. Due to the complexity of CMS it is unlikely that failed components inside the tracker will be replaced once the experiment is running. The most important wearout failure mode is likely to be the increase in threshold current, resulting from a combination of radiation damage and wearout degradation.

If the threshold current I_{thr} increases beyond the available d.c. offset bias $I_{bias}(max)$, as in Fig. 1, the optical signal would be truncated in amplitude. This would be considered a failure in an analogue link and would eventually lead to failure in a digital link if the threshold current continued to increase. The laser driver circuit therefore includes a programmable offset bias current (0-50mA range[10]), in order to track laser threshold changes during operation and provide some protection against this failure mode.

There are other possible wearout failure modes that affect the lasers, such as loss of laser efficiency, or an increase in noise, or degradation of linearity. These are ‘soft failures’, causing a degradation of the optical link performance, rather than killing the link outright.

In addition to lasers, photodiodes have also been included in this ageing study of irradiated components as they will be used in the CMS tracker for receiving digital control and timing data. However, we expect the optical receivers to be more reliable than the transmitters. The possible failure mechanisms, related to the increase in photodiode leakage current, or loss of response, can be easily compensated in the CMS tracker digital optical links. Nevertheless, the effects of ageing on irradiated InGaAs photodiodes were investigated as the reliability of these devices was unknown after irradiation.

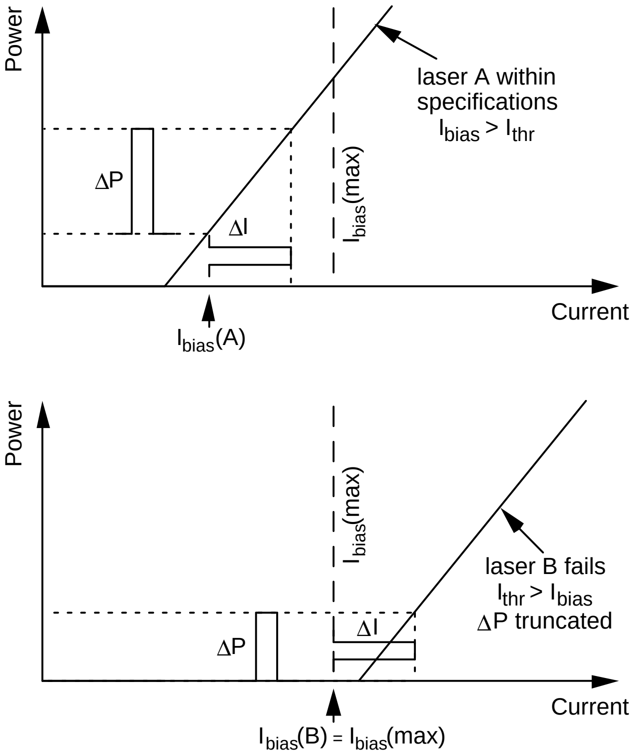

Fig. 1: Two schematic laser P-I characteristics illustrating optical link failure due to the increase in laser threshold current I_{thr}. Laser A performs within specifications whereas laser B has failed. The threshold current of laser B has increased beyond the available d.c. bias current I_{bias}(max) causing truncation of the output optical signal power ΔP.

1.3 Accelerated ageing

Since we are using pre-screened components, that have passed a burn-in test, we will not consider further the failures due to infant mortality. Mid-life random failures and old-age wearout failures are usually thermally activated[5,6] with the mean time to failure (MTTF) decreasing with increasing temperature according to the Arrhenius law,

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

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. This temperature dependence of the MTTF is the basis of thermally accelerated ageing studies.

Wearout degradation is often a small effect in a relatively short test (e.g. few thousand hours) , therefore extrapolation to some failure criteria is normally used to determine the MTTF, which is then scaled to the required working temperature using equation (1). Unfortunately there was no available activation energy data, for wearout or random failure, for the lasers tested here, and it was not possible to conduct ageing tests at different temperatures since we had a limited number of samples. Values of E_a=0.4eV[11], 0.55eV[12] and 0.7eV[13] have been measured for wearout failure in other types of 1310nm InGaAsP lasers. We have therefore based our estimates of the thermal acceleration of wearout on the most conservative of these activation energies, E_a=0.4eV. In the case of the p-i-n photodiodes tested here, the manufacturers have established a value of E_a=1.1eV[8] for wearout in unirradiated p-i-n photodiodes. For comparison, a value of 0.55eV was observed in study of InGaAs photodiodes by a different vendor[9]. For random failures, of both lasers and p-i-n photodiodes, a default value of E_a=0.35eV (proposed by Bellcore[14] in the absence of experimental data) was assumed.

There are other possible accelerating factors apart from temperature. In the case of laser ageing, the electrical bias current and optical power output can also be important acceleration factors[6]. Dissipation of electrical power in the active region by resistive heating, or through non-radiative recombination, increases the junction temperature over the ambient temperature, therefore accelerating the wearout rate. In our test, the effects of junction heating was not a significant accelerating factor since the laser bias currents were not much greater than those envisaged during the planned application.

Lasers operating at very high output power can also fail through eventual oxidation of the facets or due to catastrophic optical damage (COD) where the facet melts under increasing light absorption[6]. For InGaAsP lasers, the threshold power density required for COD (under continuous-wave operation) is more than 10MW/cm^2, significantly greater than the output power density levels in our test, so this effect should also not have been significant.

2. Ageing experiment

2.1 Devices

40 NEC 1310nm InGaAsP edge-emitting laser chips were tested. These were Multi-Quantum-Well (MQW), double-channel, planar buried-heterostructure (DCPBH) type. The devices were supplied by Italtel, mounted on planar Si-submounts and assembled in a hermetically sealed mini-DIL package, with a 2m long single-mode optical fiber pigtail. The lasers had initial (T=20°C) threshold currents of 8-15mA, and output efficiencies of around 50µW/mA for lasers 1-20 (denoted Batch 1) and 200µW/mA for lasers 21-40 (Batch 2). The difference in the efficiency values is due to different types of laser-fiber interface. In batch 1 the fiber is angle-cleaved single-mode pure-silica core with optical coupling matching the specifications for the CMS optical links[10]. For batch 2 (an earlier delivery to CERN) the devices have lensed Ge-doped fiber with a higher coupling efficiency. The type of fiber pigtail is not expected to affect either the radiation damage (at least for the fluence levels tested) or the ageing behavior.

30 Epitaxx 75µm active diameter, back-illuminated, planar InGaAs photodiodes were used in the ageing test. The devices were supplied by Italtel in an identical type of package as the lasers, with standard Ge-doped fiber pigtails. The p-i-n photodiodes all had initial leakage currents of around 10pA (at 20°C, -5V), and typical responsivities of 0.9A/W at 1310nm.

2.2 Irradiation

30 lasers (10 from batch 1 and 20 from batch 2) were irradiated and 10 (from batch 1) were kept unirradiated. 19 p-i-n photodiodes were irradiated and 11 were kept unirradiated. The irradiated devices were exposed at room

temperature to neutrons (with a mean energy of 6MeV) at the SARA facility at ISN, Grenoble[15], as outlined in Table 1.

The total neutron fluences of the same order of magnitude (>10^{14}n/cm^2) as the maximum expected hadron fluence (pions, neutrons, protons etc. combined) in the CMS tracker over 10 years of operation. The gamma background per 10^{14}n/cm^2 was 1.8kGy[15] though damage due to ionizing radiation in these devices was previously found to be negligible (up to 100kGy) compared to damage after 10^{14}n/cm^2[16,17]. The irradiated samples were then stored, electrically shorted, at room temperature for up to 15 months before the ageing test. Based on our earlier studies[17,18], we estimate that 30% of the initial radiation damage in both the lasers and photodiodes annealed during this period.

During irradiation the lasers were biased at 5-10mA above threshold and the p-i-n photodiodes were biased at -5V. The laser threshold currents were measured at periodic intervals during the irradiation, allowing the threshold current changes to be tracked and the bias currents to be adjusted. The threshold currents of the irradiated lasers just before ageing are compared to pre-irradiation values in Fig. 2, where the increase caused by radiation damage is clearly apparent. Fig. 3 shows the leakage current of the irradiated photodiodes at 20°C, at -5V bias, just before the ageing test commenced. The increase in leakage current due to radiation damage is large compared to the typical value of 10pA before irradiation. A thorough discussion of the radiation damage effects for these particular types of laser and photodiode can be found in other reports[3,4,16], for tests carried out using neutrons and other radiation sources.

Devices	Source	Date	Fluence range ($\times10^{14}$n/cm^2)	Exposure time (hours)	Annealing time (days)
10 (out of 20) InGaAsP Lasers (Batch 1)	ISN Grenoble, SARA facility <E_n>=6MeV	11/97	4.1 to 6.1	185	197
20 (out of 20) InGaAsP Lasers (Batch 2)		6/97	2.4 to 3.9	94	412
19 (out of 30) InGaAs Photodiodes		6/97	1.2 to 2.5	94	366 – 412 (devices aged in 2 groups)

Table 1: Summary of irradiation details. Devices received various fluences due to their different positions with respect to the source. The annealing time shown is the time between irradiation and the start of ageing of the samples.

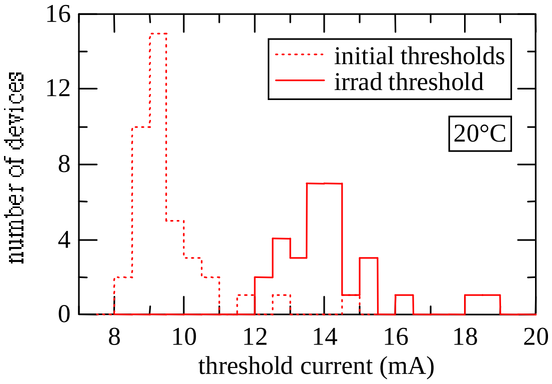

Fig. 2: Threshold currents for the irradiated lasers. Data shown are the pre-irradiation values and those measured just before ageing (i.e. after irradiation and annealing).

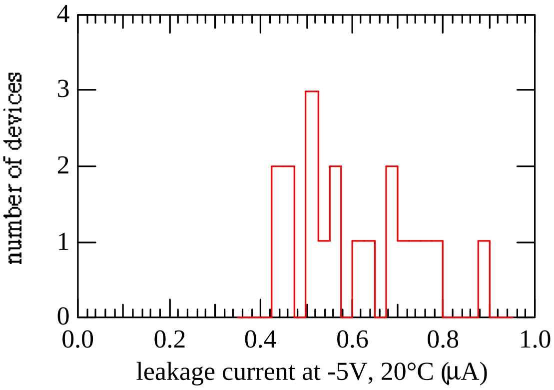

Fig. 3: Leakage currents in irradiated p-i-n photodiodes. Pre-irradiation values were ~10pA at –5V, 20°C.

2.3 Ageing test setup

The lasers and photodiodes were operated at 80°C for approximately 4000 hours. The ageing test is illustrated in Fig. 4. The lasers and p-i-n photodiodes were not aged all at once. The test was started with 20 lasers (10 unirradiated and 10 irradiated from batch 1) and 20 p-i-n diodes (10 unirradiated and 10 irradiated). The other 20 lasers and 10 p-i-n photodiodes were added later (after 600 hours), when it was clear that degradation rates were very small. Had the rates been significantly larger, the other devices could have been aged later at a different temperature in order to estimate the temperature dependence of the wearout degradation.

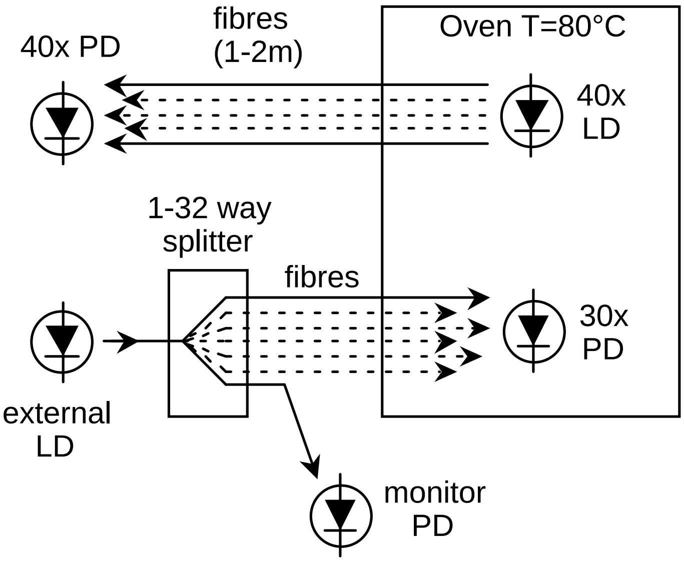

Fig. 4: Schematic arrangement of the optoelectronic devices in the ageing test. LD = laser diode (all 1310nm InGaAsP), PD = InGaAs photodiode.

The laser output (L-I) characteristics versus applied current (0-75mA range, in 1.5mA steps at 2 seconds per step) were measured every 2 hours. Between these measurement cycles, the lasers were continuously biased at 60mA, such that all the devices were biased above threshold. The laser threshold currents were roughly 2.5 times larger at 80°C than at 20°C, since the threshold current I_{thr} increases roughly exponentially with temperature[19],

$$I_{thr}(T) = I_0 \exp(T/T_0) \tag{2}$$

with the characteristic temperature T_0 ~60K for the lasers in this test, typical of 1.3µm InGaAsP lasers[19].

For the p-i-n photodiodes, leakage current and photocurrent were also measured at 2 hour intervals. The leakage current was measured at –5V bias without illumination. The photocurrent was measured at different power levels up to ~150µW, by ramping the current in an external 1310nm laser. Another p-i-n photodiode, situated outside the oven, was used to monitor any variation in the external laser characteristics. Between measurement cycles the photodiodes were operated at -5V bias and illuminated with ~100µW optical power.

3. RESULTS

3.1 Lasers

The laser threshold current versus time is shown in Fig. 5 for all the devices tested. At 80°C the unirradiated devices have initial threshold currents of 21-31mA and the irradiated devices have values of 28-55mA, this larger variation being mainly due to the different neutron fluences received by the various devices. Overall the rates of wearout degradation, in terms of threshold current increase, are very small, <0.4mA/1000hours in the unirradiated devices. For the irradiated devices, annealing of the radiation damage was the main effect. Only a few of the irradiated devices had increases in threshold current. The device labeled A, which has the most degradation, should have actually been rejected by the supplier following burn-in.

The laser efficiency measurements are shown in Fig. 6. Only a few devices show any degradation, in terms of a loss of efficiency. Apart from device A, which should not be included in the analysis, the worst degradation rate (gradient of a line fitted from 2000<t(hrs)<4000) corresponded to 1.3%/1000hrs. Annealing effects again dominate for the irradiated devices.

The irradiated lasers continued to anneal throughout the 4000 hours at 80°C, therefore the ageing related wearout was obscured for these devices and a wearout rate could not be accurately determined. However, as the annealing rate decreases with increasing time[16,18], the results suggest that the wearout rate of the irradiated lasers is not significantly greater than in the unirradiated samples.

3.2 P-i-n photodiodes

The p-i-n leakage current and photocurrent results are shown in Figs. 7 and 8 respectively. The leakage current increases with temperature and is roughly 20 times greater at 80°C than at 20°C. The photocurrent data are plotted for an incident optical power of approximately 120µW (corrected for fluctuations in the external laser power). The 80°C data are the same as that found for 20°C since the response of these devices was not affected by the increase in temperature. None of the irradiated photodiodes had been exposed to a sufficiently high neutron fluence to cause a significant decrease in responsivity[17]. Overall, there was no significant ageing-related degradation in any of the p-i-n photodiodes in terms of increased leakage current or decreased photocurrent.

4. Failure rates and predictions for the CMS tracker components

4.1 Wearout failure

Only the unirradiated lasers exhibited a clear wearout effect. For the irradiated lasers the annealing of the radiation damage masked any wearout degradation. In the case of the p-i-n photodiodes there was no significant wearout in any of the samples. In order to calculate the MTTF for this particular type of lasers in the CMS tracker environment we have assumed that the effects of radiation damage and wearout can be considered separately. This assumption is justified since there we concluded that there was no significant extra degradation in the irradiated lasers. We will therefore use the wearout rates for the unirradiated lasers, combined with the expected maximum radiation damage, to determine a worst-case MTTF for lasers inside CMS.

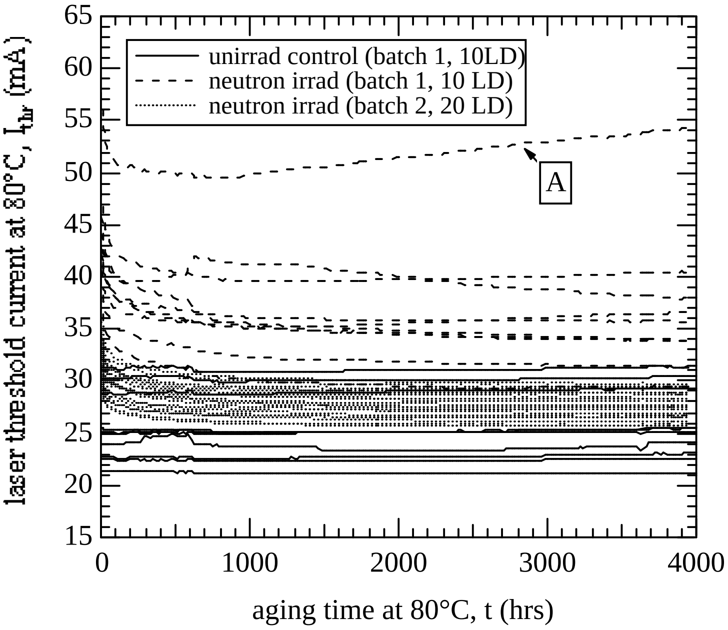

Fig. 5: Laser threshold current during ageing.

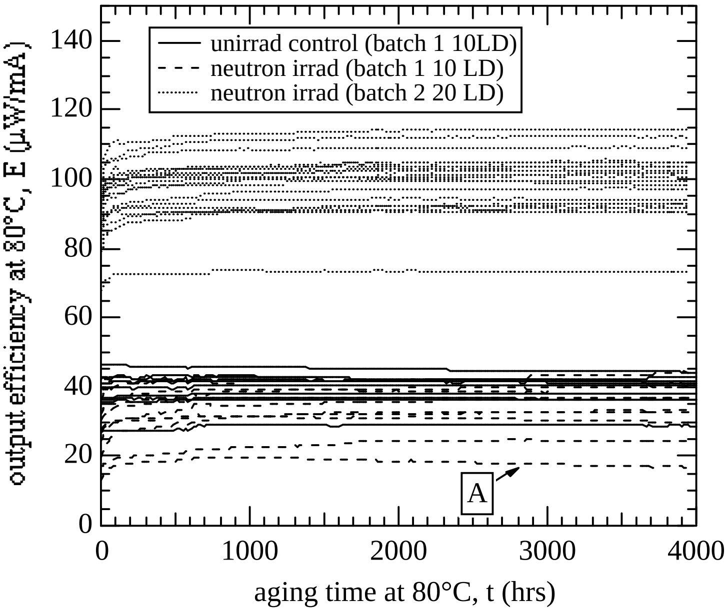

Fig. 6: Laser efficiency during ageing.

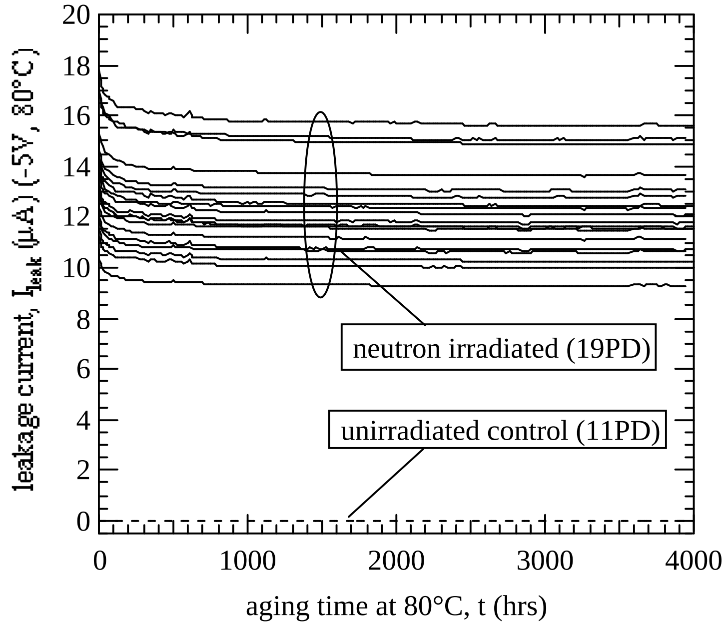

Fig. 7: P-i-n leakage currents during ageing.

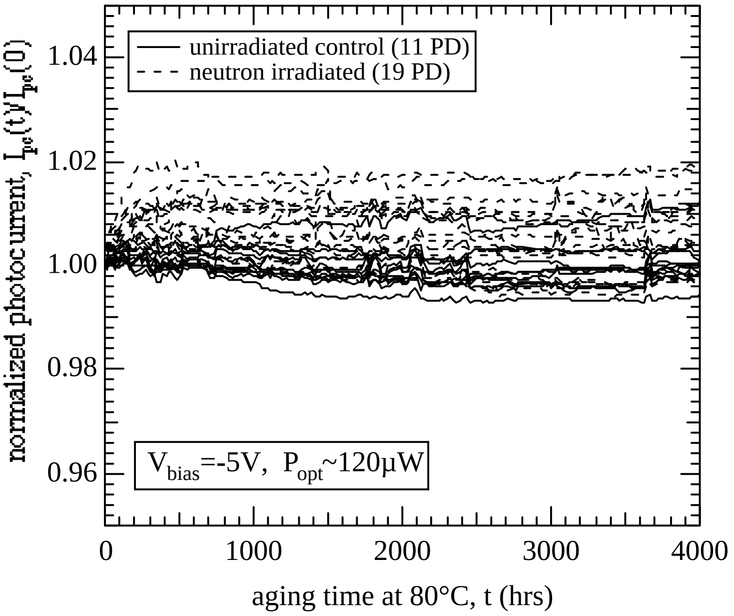

Fig. 8: P-i-n photocurrents during ageing. The results are normalized relative to the value at the start of ageing.

4.1.1 Failure criteria

We will introduce a failure criteria related to the failure mode shown in Fig. 1, such that the laser threshold current should remain below the specified maximum d.c. bias, I_{max}=50mA[10] at 20°C. Other failure criteria could also be applied, such as a limit of the laser efficiency loss. However this degradation mode is less important than the threshold increase since the efficiency loss can be compensated by increasing the gain at either the laser driver or receiver, whereas the maximum d.c. bias is a fixed limit.

For the lasers studied, the initial laser threshold current I_{init} was <15mA at 20°C. From our previous radiation damage studies[3,4,18], we estimate that the threshold increase at 20°C due to radiation damage will be limited to ΔI_{rad}<10mA. This considers the worst-case exposure, and includes annealing over a period of 10 years of CMS operation.

Assuming that the increases in threshold current due to radiation damage and wearout can be considered separately, the failure criteria for the limit in the increase of threshold current due to wearout is

$$\Delta I_{wear} = I_{\max} - I_{init} - \Delta I_{rad} \tag{3}$$

The maximum allowed increase due to wearout at 20°C is therefore ΔI_{wear}(20°)=50-15-10=25mA. Using expression (2) this can be converted to a limit that can be applied to ageing at 80°C, that is ΔI_{wear}(80°)=67mA.

4.1.2 Wearout MTTF at 80°C

The degradation rate was defined as the slope of a line fitted to the data (between 2000 and 4000 hours, to avoid any burn-in related effects). The mean degradation rate for the unirradiated lasers was 0.14mA/1000 hours at 80°C, with a standard deviation of 0.03mA/1000hours. The (linearly) extrapolated MTTF, based on a criteria of ΔI_{wear}=67mA, is therefore 4.6(±1.0)x10^5 hours at 80°C. Laser wearout failures typically follow a log-normal failure distribution[5,6] though further ageing tests, with a larger number of devices, will be necessary to determine if this distribution describes the lasers tested.

4.1.3 Accelerating factors and MTTF in the CMS tracker

The CMS tracker will be operated at -10°C in the silicon detector layers and 20°C in the gas microstrip detector layers[2]. Table 2 shows the MTTF at 80°C and the subsequent MTTF values at 20°C and -10°C obtained using expression (1) and the assumed activation energy value of E_a=0.4eV[11].

E_a (eV)	T (°C)	acceleration factor	MTTF (10^5hrs)
-	80	-	4.6
0.4	20	X 15	69
	-10	X 90	410

Table 2: Calculated wearout MTTF of lasers at CMS tracker temperatures based on E_a=0.4eV

For the -10°C value of MTTF, the result is more approximate as the parameters in equation (3) are not all the same as at 20°C hence there is not an equal margin for wearout degradation. The maximum d.c. bias limit remains 50mA, but the radiation damage may be greater at -10°C than 20°C since annealing is a thermally activated process. (Tests are underway to determine the actual temperature, and electric current, dependence of annealing.) However, the overall MTTF at -10°C may not be significantly changed, since the increased threshold damage will be balanced to some extent by the decrease in the threshold due to the lower temperature, following equation (2).

In summary, the MTTF values for wearout are much longer than the expected operating time, which will be approximately 40000 hours over 10 years. The 0-50mA threshold current tracking capability of the laser driver circuit should be sufficient to ensure that very few of the transmitters would fail due to wearout in CMS (if these particular lasers are used), despite the additional degradation due to radiation damage.

4.2 Random failure rates

In this ageing test none of the devices failed suddenly. An upper bound for the probability of random failure (for these particular types of laser and photodiode, under these specific test conditions) can therefore be determined using Poisson statistics, based on the number of device-hours accumulated without failure[5].

For zero failures in a sample group of *n* devices, as we found in this test, the upper bound of the failure rate p_u that applies to any device taken from the lot that was sampled, is given by

$$p_u = \left(\frac{1}{n}\right)\ln\left(\frac{1}{1-C(0)}\right) \tag{4}$$

where $C(0)$ is the confidence level (C.L.).

4.2.1 Random failure probability at 80°C

Table 3 shows the calculated upper bounds on the probability of failure p_u at 90% C.L. for the different sample groups of lasers and p-i-n photodiodes respectively. Some care is required in interpreting the results, which appear to indicate, for example, that the lasers are more reliable than p-i-n photodiodes in terms of random failure. This is, in fact, simply due to the number of devices tested; more lasers were tested than p-i-n photodiodes hence a lower failure rate limit is calculated for the lasers.

(a)

laser group (no. devices)	p_u (90% C.L.)
irradiated (30)	0.077
control (10)	0.23
all combined (40)	0.058

(b)

p-i-n group (no. devices)	p_u (90% C.L.)
irradiated (19)	0.12
control (11)	0.21
all combined (30)	0.077

Table 3: Upper limits of random failure probability p_u in (a) lasers and (b) p-i-n photodiodes at 80°C.

4.2.2 Random failure rates inside the CMS tracker

For the extrapolation of the random failure rates to other operating temperatures the failure mechanisms are assumed to be thermally activated with an activation energy of 0.35eV[14] for both lasers and photodiodes. Table 4 gives the values for the upper bound of failure rate *F* at temperatures of 20°C and -10°C, based on the 80°C data. The conversion into the failure rate unit of FITs, (1FIT = 1 failed device per 10^9 device-hours), has been made using

$$F(FITs) = \frac{p_u \times 10^9}{t_{ageing}} \tag{5}$$

where the test time t_{ageing} is taken to be 4000 hours, and p_u is the failure probability (upper limit for 90% C.L.)

calculated for the particular temperature.

For the optical link components used inside the CMS tracker it is considered that 1% per year will be the maximum tolerable failure rate for the whole system. For an annual operational time of ~4000 hours, this gives a limit of 2500FITs, therefore it is likely that the devices tested have a low enough random failure rate, even after irradiation, for use in the CMS tracker.

E_a (eV)	T (°C)	acc. factor relative to 80°C	F (lasers) (FITs)	F (p-i-n's) (FITs)
-	80	-	15000	19000
0.35	20	x11	1400	1800
	-10	x51	280	380

Table 4: Calculated upper bounds (90% C.L.) on random failure rates based on an activation energy of E_a=0.35eV.

The results for random failure are, in principle, limited to these specific test conditions of isothermal ageing. We have not stressed the devices sufficiently to measure all the possible random failure modes. Sudden failures are often detected using different test conditions, such as thermal cycling and mechanical shock testing. These tests have already been carried out by Italtel, on significant numbers of lasers and p-i-n photodiodes in mini-DIL packages, without any device failures. Inside the CMS Tracker the devices will be operated in a constant temperature, vibration free environment therefore the test results presented here should be relevant to this application.

5. Conclusion

A first accelerated ageing test has been carried out on candidate InGaAsP lasers and InGaAs p-i-n photodiodes for the CMS tracker optical link application, investigating both irradiated and unirradiated devices. The irradiated devices had neutron fluences $>10^{14}$n/cm^2, typical of the maximum expected particle fluences inside the tracker over 10 years. The ageing test involved storing the devices under electrical bias for 4000hours at 80°C.

Wearout related degradation effects in the lasers, normally characterized by threshold current increases and efficiency decreases, were very small. For the p-i-n photodiodes there was no significant degradation at all, with no decrease in the photocurrent and no increase in the leakage current. In all the irradiated devices, the main observable effects were due to annealing of some of the radiation damage, which masked any degradation effects.

No random failures, sudden catastrophic device failures not related to wearout, occurred in this test for either lasers or p-i-n photodiodes.

The wearout and random failure rates have been assumed to be temperature activated and the devices were assumed to be representative of the larger device population. If these assumptions are appropriate, and the CMS Tracker environment introduces no other risks, the wearout and random failure rates of optoelectronic devices inside the CMS tracker will be very small.

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