Radiation Hardness Qualification of InGaAsP/InP 1310-nm Lasers for the CMS Tracker Optical Links

Karl Gill, Robert Grabit, Jan Troska, and Francois Vasey

***Abstract*—The series of validation tests for radiation hardness qualification of lasers for use in 46 000 optical links of the CMS Tracker detector at CERN, Geneva, Switzerland, are presented. These tests included accelerated radiation damage, annealing, and aging studies, simulating the effect of doses and fluences, up to 2×10^{14} particles/cm^2 and 100 kGy, accumulated over a ten-year operating lifetime. The worst-case damage effect, in lasers operating closest to the beam-collision point, is expected to be a threshold current increase of under 6 mA. The lasers tested therefore qualify as being sufficiently radiation hard. The qualification tests also form the basis of future radiation hardness assurance of lasers during final production. An advance validation test of lasers from candidate wafers is defined that will confirm the radiation hardness of lasers before a large number of transmitters are assembled from these wafers.**

***Index Terms*—CMS experiment, high energy physics, lasers, optical links, radiation hardness.**

I. Introduction

RADIATION damage is one of the main technical challenges in the development of the latest generation of high-luminosity colliding-beam experiments. This concern motivated the creation of several research and development (RD) programs at CERN, Geneva, Switzerland, during the last decade, focused specifically on development of radiation hard components and systems for the Large Hadron Collider (LHC) experiments.

RD23 was one such program with an aim to develop a fiber-optic link system for large-scale transmission of analogue data from the detectors in the LHC experiments [1]. It was necessary to demonstrate that fiber-optic link technology could be adapted to the specific needs of LHC experiments and then that the link components were sufficiently radiation resistant for LHC conditions.

Building on the efforts of RD23, both analogue and digital optical link systems, have since been developed at CERN to read out and control approximately tenmillion silicon microstrip detectors in the Tracker of the Compact Muon Solenoid (CMS) Experiment [2]. A total of 43 000 analogue links transfer 4×10^7 samples/s/fiber from the detectors, which are distributed throughout the $\sim$ 25-m^3 Tracker volume, to the back-end data-acquisition system. In addition, 2600 digital links will transmit the 40-MHz LHC clock and CMS Level-1 trigger signals at 80 Mbit/s and control signals to and from the Tracker at 40 Mbits/s [2].

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The authors are with CERN EP Division, Geneva 23, Switzerland (e-mail: karl.gill@cern.ch).
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In order to minimize the resources required to develop and produce such a large number of optical links, the systems are almost completely made up of commercial off-the-shelf (COTS) components or devices based closely on COTS. For example, the laser die, submount, optical fiber pigtail, and connector are all COTS, but the compact final form of the laser package, described elsewhere [3], is specific to this application. In contrast, both a linear laser driver [4] and digital receiver [5] ASIC have been custom developed for this application at CERN, in 0.25-μm technology [6], in order to satisfy radiation hardness requirements.

For the COTS components, there are no manufacturers' guarantees of radiation hardness because these components are typically manufactured for telecommunications applications, operating in relatively benign environments. The optical link components located inside the CMS Tracker will also be practically inaccessible for maintenance during most of their ten-year lifetime. All of the optical link components considered for use in the Tracker have therefore been validated for radiation hardness [7]–[10] up to the worst-case doses and fluences expected. At the center of CMS, where the Tracker is located, the radiation field will be at its most intense. Total particle fluences will be up to $2 \times 10^{14}/\text{cm}^2$ over a ten-year operating lifetime, dominated by pions with energies peaked around 300 MeV, in addition to an ionizing dose of 100 kGy [2].

The link specifications [3] have therefore been tailored during the development phase of the project in order to be able to compensate for radiation damage effects, once these effects had been quantified. The laser driver ASIC is a good example: it is specified to have a programmable output dc bias-setting, which allows any change in threshold current of a laser due to radiation damage or wearout to be tracked and compensated up to a laser threshold current of 45 mA [4].

It should be noted that the other remaining aspects of the CMS Tracker environment, namely, the low temperature (approximately -10°C), dry nitrogen atmosphere, and 4T magnetic field do not require any special considerations with respect to the optical links, apart from the use of nonmagnetic materials. The operating temperature is within the usual limits of telecom component specifications, and it has also been demonstrated that the strong magnetic field does not influence the optical link performance [11]. In addition, optical link components being considered for use inside CMS that were found to be magnetic were disqualified.

The harsh operating environment within the CMS Tracker, coupled with the large volume of components, remain the main challenges to the successful completion of the project. For the lasers, these challenges have been, and are being, tackled in two

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TABLE I
EXPERIMENTAL CONDITIONS FOR THE SEQUENCE OF RADIATION DAMAGE, ANNEALING, AND AGING STUDIES WITHIN THE RADIATION HARDNESS QUALIFICATION

Test	No. lasers	Dose or particle fluence (±10%) (averaged over devices)	Irrad time (hrs)	Annealing time (hrs)	Irradiation conditions (bias and temperature)	Post-irradiation conditions (bias and temperature)
A.1	4	100kGy (^{60}Co-γ)	46	8	Biased at 5 to 10mA above threshold, Ambient T (20-30°C)	Biased at 5 to 10mA above threshold, Ambient T (20-30°C)
A.2	4 (same as for Test A.1)	10.8×10^{14}n/cm^2 (mean neutron energy = 0.8MeV)	6.5	115	Biased at 5 to 10mA above threshold, Ambient T (20-30°C)	Biased at 5 to 10mA above threshold, Ambient T (20-30°C)
A.3	4	$1.1\times10^{14}\pi$/cm^2 (pion momentum = 300MeV/c)	32	120	Biased at 5 to 10mA above threshold, Ambient T (20-30°C)	Biased at 5 to 10mA above threshold, Ambient T (20-30°C)
A.4	2	4.5×10^{14}n/cm^2 (mean neutron energy = 20MeV)	3.2	74	Biased at 5 to 10mA above threshold, Ambient T (20-30°C)	Biased at 5 to 10mA above threshold, Ambient T (20-30°C)
B.1	6	As for Test A.4			Unbiased, Ambient T (20-30°C)	Biased (0,30,60mA, 2 devices per current value) Ambient T (20-30°C)
B.2	12	4.0×10^{14}n/cm^2 (mean neutron energy = 20MeV)	3.5	16 (at –13°C) 500 (at other temperatures)	Unbiased, Cooled (-12°C)	Unbiased, Heated (T=20,40,60°C, 4 devices per T value)
C	12 (same as for Test B.2)	As for test B.2				Test B.2, followed by ageing: T=80°C, I=60mA, t=2500 hrs

stages. The first step was the sequence of validation tests carried out to qualify the lasers for radiation hardness prior to production. This work is described in Section II. The second step has been the definition of an advance validation test (AVT) sequence for the radiation hardness assurance of the large number of lasers that will be used to assemble the final optical links. This step is described in Section III.

II. Radiation Hardness Qualification

The aim of the qualification was to prove that the lasers finally selected [1] for the application were indeed sufficiently radiation hard. This was necessary because the selection was based partly on radiation effects measured during early validation tests on only a small number of samples. These studies, Tests A.1 and A.2 in this paper, were part of the CERN Market Survey of laser transmitters, which was the first step of a series of formal commercial actions.

The radiation hardness qualification procedure involved a series of accelerated tests: (a) damage measurements using various radiation sources, with the lasers operating under conditions simulating the final application; (b) annealing measurements as a function of bias and current; and (c) aging measurements. These tests are summarized in this section, and further details of the experimental procedures and radiation sources used are given elsewhere [12].

The criterion for qualification was that the lasers should operate according to their specifications [3] throughout the whole lifetime of the optical links. The results from these accelerated tests were therefore extrapolated to extend over the full lifetime of the links in order to determine if the qualification was passed.

Altogether, 28 lasers were used in this series of tests, with the tests labeled Test A through Test C, as in Table I. The choice of the number of devices tested is discussed in Section IV. The lasers were packaged in their final form, as specified for the Tracker optical links [3], i.e., compact, nonmagnetic packages with single-mode fiber pigtail. The initial laser threshold currents were around 5 mA at 20°C, and the output efficiencies (out of the fiber) were $\sim$ 40 μW/mA, as specified for the application [3]. All of the devices had been subjected to a burn-in and a test procedure at the supplier before delivery to CERN.

A. Radiation Damage Tests

Tests A.1–A.4 were measurements of radiation damage and annealing with ^{60}Co-gammas (4 lasers), 0.8-MeV neutrons (4 lasers), 300-MeV/c pions (4 lasers), and 20-MeV neutrons (2 lasers), respectively. For both neutron sources, these quoted energies are mean values. Overall, these sources were chosen as this set of particle species and energies represents some of the main parts of the radiation spectrum that will be encountered inside the CMS Tracker [2].

Irradiations in Test sequence A were made under similar conditions to previous tests made with other devices [7]–[10], i.e., with the lasers irradiated at room temperature and biased a few milliamps above threshold during and after irradiation. The lasers were connected both optically and electrically, in order to measure the damage and subsequent annealing effects in situ [12]. The L-I (and V-I) characteristics were measured at intervals during the tests, allowing the parameters such as the threshold current, efficiency, and laser voltage to be tracked in time.

[1]The laser type selected for the CMS Tracker Optical Links is Mitsubishi Type ML7XX8 multi-quantum-well, 1310-nm edge-emitting laser, supplied by ST Microelectronics in a compact, nonmagnetic custom package.

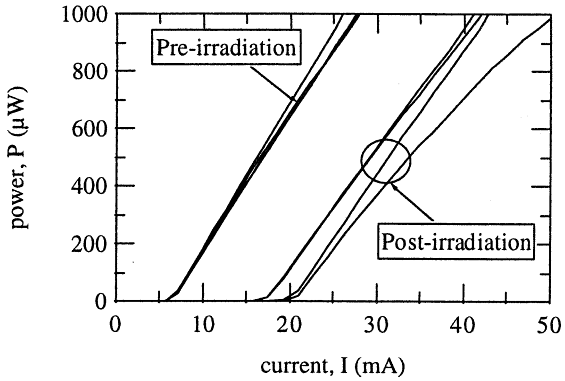

Fig. 1. Laser characteristics before and after 1.0×10^{15} n/cm^2 in Test A.2.

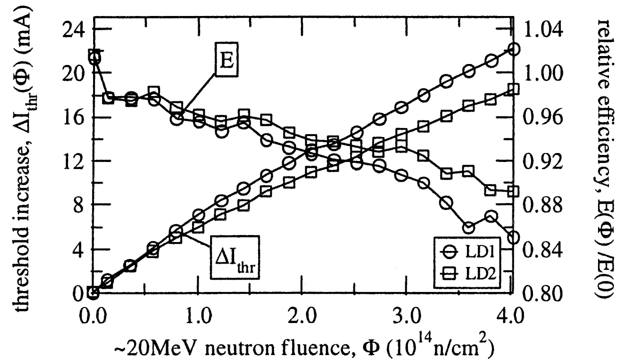

Fig. 2. Laser threshold and efficiency damage versus accumulated neutron fluence in Test A.4.

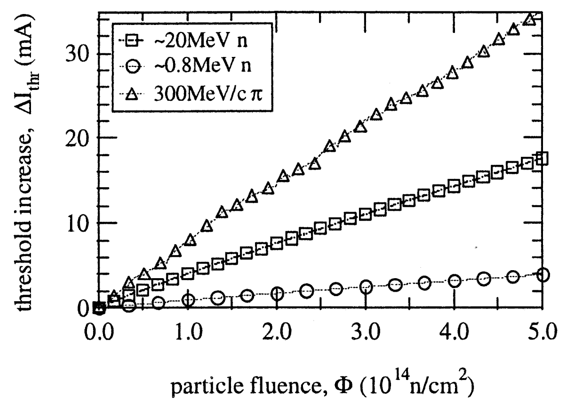

Fig. 3. Average threshold current increase compared for various sources: 0.8-MeV neutrons, ~ 20-MeV neutrons, and 300-MeV/c pions. The plots are based on normalization of the measured data to a fluence of $5\times10^{14}/\text{cm}^2$ over 96-hour duration.

Ionization damage from ^{60}Co gammas up to a dose of 100 kGy in Test A.1 caused no significant damage [12]. However, in the other tests, there was significant damage with the main effects being an increase in threshold current and a decrease in output efficiency. These are illustrated in Fig. 1, which shows data from Test A.2. These effects are consistent with those observed in all of our previous studies on various types of 1310-nm lasers [7]–[10]. The threshold increase and efficiency loss typically only occur with particles that can cause displacement damage, e.g., neutrons, protons, or pions. Both effects are related to a degradation of carrier lifetime [13], [14] due to introduction of defects in the active volume, as is the case in many types of irradiated semiconductor components.

In this particular series of tests, we focus on the effect of the damage to the laser threshold current, as this parameter was the one most affected by radiation damage. The other key parameter in terms of the optical links application is the output efficiency. Our measurements have shown that the degradation of the efficiency by displacement damage is directly proportional to the threshold current damage [7]. In this particular type of laser, there is approximately 1% loss of efficiency per 1-mA increase in threshold current, as illustrated in Fig. 2, which shows data from Test A.4.

The threshold current increase due to radiation damage from the two neutron sources, and the pion source is compared in Fig. 3. The average measured damage in the devices tested is used and normalized for a total particle fluence of $5\times10^{14}/\text{cm}^2$ accumulated in a 96-hour irradiation period. This normalization procedure, described elsewhere in more detail [10], [12], makes use of the damage and annealing data from a given test and extrapolates the results to these normalized conditions being considered here.

We have then defined relative displacement damage factors as the ratios of the threshold current increases measured with the different sources. Overall, 300-MeV/c pions are 1.9 times more damaging than 20-MeV neutrons (average energy), and 8.3 times more damaging than 0.8-MeV neutrons (average energy). The uncertainty is $\sim 25\%$ in each case, based on the combined uncertainty in the dosimetry and the spread of data over the samples used in a given test. These ratios are similar to those measured for InGaAsP/InP 1310-nm lasers from two other manufacturers, measured under identical conditions (authors' unpublished data), even though the absolute threshold shifts were different by up to a factor 2.

B. Annealing

We now summarize briefly the accelerated annealing tests, and full details of the procedures are given elsewhere [12]. Test B.1 was a measurement of the annealing rate in six lasers at various bias current settings following 20-MeV neutron damage. The irradiation was made without bias, except during L-I measurement cycles.

The effect of bias-enhanced annealing in irradiated AlGaAs/GaAs lasers has been reported recently [15], and any significant acceleration of annealing in InGaAsP/InP lasers would have important consequences for lasers used inside the CMS tracker, such that the long-term accumulation of radiation damage might be suppressed by applying larger dc bias currents. The annealing results of Test B.1 are shown in Fig. 4, where the fraction of remaining damage F is defined as the ratio of threshold current damage ΔI_{thr} remaining after some annealing to that at the end of irradiation

$$F(t_{anneal}) = \frac{\Delta I_{thr}(t_{anneal})}{\Delta I_{thr}(\Phi, t_{irrad})}. \quad (1)$$

The annealing at 60-mA bias was accelerated by a factor of ~ 10 compared to lasers annealed without a dc bias current. It

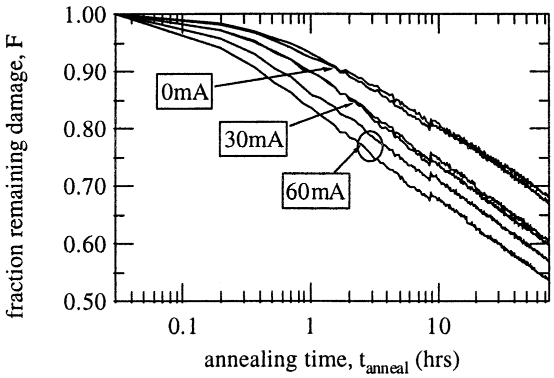

Fig. 4. Annealing of threshold damage after neutron irradiation for different bias current values in Test B.1.

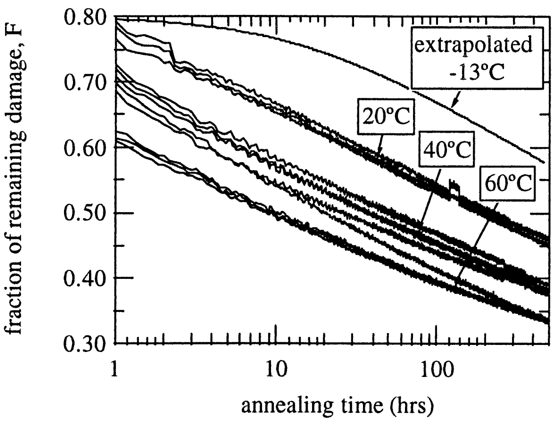

Fig. 5. Annealing of laser threshold damage at various temperatures in Test B.2.

should be noted that this acceleration is quoted in terms of the amount of time required to reach a certain level of annealing; i.e., the whole annealing curve shifts by one decade in time, when time is plotted on a log scale as in Fig. 4. Despite this large acceleration factor, the annealing is spread over many orders of magnitude in time and the additional annealing at higher currents results in only a minor change in the amount of fractional damage that is recovered. It had been hypothesized that it might be possible to accelerate the annealing of damaged lasers in the final system by using currents $\sim$ 60 mA, although it would now appear that this idea offers little benefit.

For the next part of the experimental study, which measured annealing at elevated temperatures in Test B.2, 12 lasers were irradiated with 20-MeV neutrons to between 3.5 and $4.4 \times 10^{14}/\text{cm}^2$, at a temperature of -13°C. As well as preparing devices for the annealing study, it was also considered important at this time to check the damage levels at a temperature close to that expected inside the CMS Tracker (-10°C). The damage data were indeed used in the calculation of the expected effects over the full lifetime of the lasers [12].

The annealing study then consisted of taking the devices in groups of 4, and measuring the annealing at temperatures of 20, 40, and 60°C during 500 h. The results are shown in Fig. 5, along with an extrapolation of the average annealing measured in the 14 h after irradiation at -13°C to 500 h. Some 20% annealing had already taken place in the 14 h following irradiation; hence, the vertical scale has a maximum value of 0.8.

The annealing is clearly thermally activated, with the recovery after a given time being greater at higher temperatures. Interestingly, the instantaneous rates (dF/dt) are similar at different temperatures and the overall annealing behavior is approximately linear with log(annealing time). The same effect was observed in the other damage tests with pions and neutrons earlier in the qualification study [12], as well as in previous studies on lasers from a different manufacturer [10].

Thus far, it has not been possible to fit the annealing data of Test B.2 with an activation energy model such as that used in our previous studies on another type of 1310-nm InGaAsP/InP laser [10], which was based on an earlier model of annealing in irradiated photodiodes [16]. This part of the investigation is noted as an area for future work, especially as we depend on the annealing data in order to make the long-term predictions of the overall radiation damage expected for lasers in the CMS Tracker application.

Nevertheless, despite our incomplete understanding of the annealing effects and the underlying defect kinetics, some very important conclusions can still be reached that are particularly relevant to the radiation hardness qualification.

As up to $\sim 65\%$ of the damage is annealed at 60°C, we consider that it is reasonable to assume that the extrapolation of the -13°C data can be extended up to $\sim$ 50 000 h, with an expectation that the total damage remaining would be $\sim 35\%$ of the initial damage. This very long annealing timescale is similar to the intended operational lifetime of the lasers in the CMS Tracker, i.e., ten-years (or 88 000 h). Therefore, the accelerated annealing data can be used with reasonable confidence to predict the recovery of damage in the final system over the full lifetime of the links.

C. Aging

Test C then measured the effect of accelerated aging on the 12 devices already irradiated and (partially) annealed in Test B.2. The lasers were operated with 60-mA bias, at a temperature of 80°C, for 2500 h. The results are shown in Fig. 6. Wearout-related degradation is often manifested as an increase in the threshold current [17]. No increase was observed in this test, particularly toward the end of the test when the effect of the continued annealing was attenuated.

A mean-time-to-failure (MTTF) could not be calculated using the usual technique of extrapolation of the threshold current to some operational limit, because no degradation was observed. The 2500 h ageing period at 80°C is similar to $\sim 10^6$ h at -10°C in the CMS Tracker, if it is assumed that wearout is governed by the Arrhenius Law and has an activation energy of 0.4 eV. This is the value recommended by Bellcore [18] for any case where the real activation energy is unknown.

It is therefore considered highly unlikely that, during the CMS Tracker lifetime, many lasers will fail due to an increase in threshold current caused by wearout-related degradation, despite the lasers being damaged by exposure to radiation.

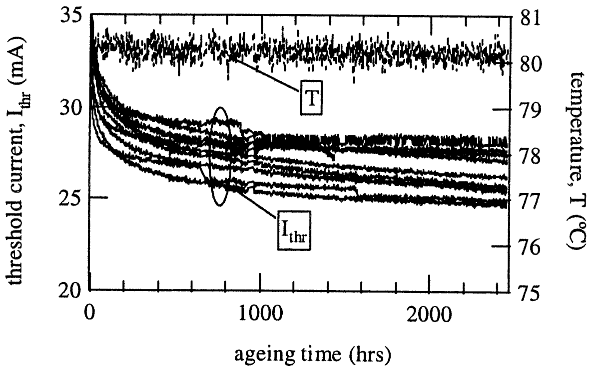

Fig. 6. Laser threshold current measured during accelerated aging step at 80°C in Test C.

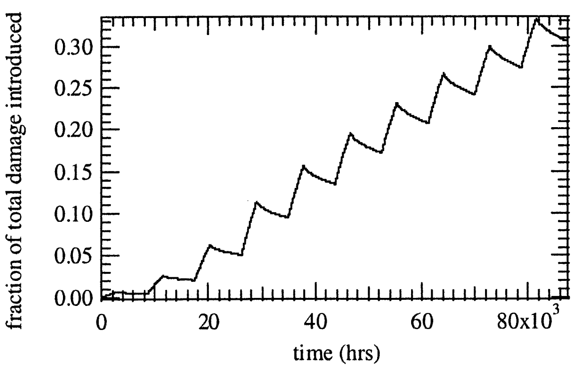

Fig. 7. Damage and annealing profile expected during the first ten years of LHC running.

D. Prediction of Damage During the First Ten Years of LHC Operation

We recall that the radiation hardness qualification criterion for the lasers was that they should perform according to the specifications [3] during the entire ten-year lifetime of the system. To determine finally whether the lasers qualified, we used a combination and extrapolation of the data from the previous accelerated validation tests. A detailed description of the extrapolation procedure is given elsewhere [10], [12], and here we focus on the worst-case position of lasers near the center of the CMS Tracker, which is the most stringent condition in terms of the qualification of the laser.

The data for the damage and annealing extrapolated from Test B.2 at -13°C was used to build up a profile of the damage and annealing expected at close to -10°C over a ten-year period (88 000 h) of operation inside the Tracker. The resulting profile is shown in Fig. 7. It also includes the expected ramping up of the accelerator performance over the first few years [2], and the plan to operate the LHC only for around five months per year.

The calculation of the actual threshold increase expected for a laser in a particular position in the Tracker was then based on this profile, which was used to scale the total damage expected to be caused by the fluence of particles at that point in the Tracker. The relative damage factors (measured in Test sequence A) were then used for an estimate of the damage contribution from the most important particle species, namely, $\sim$ 300-MeV pions and $\sim$ 1-MeV neutrons in the CMS Tracker.

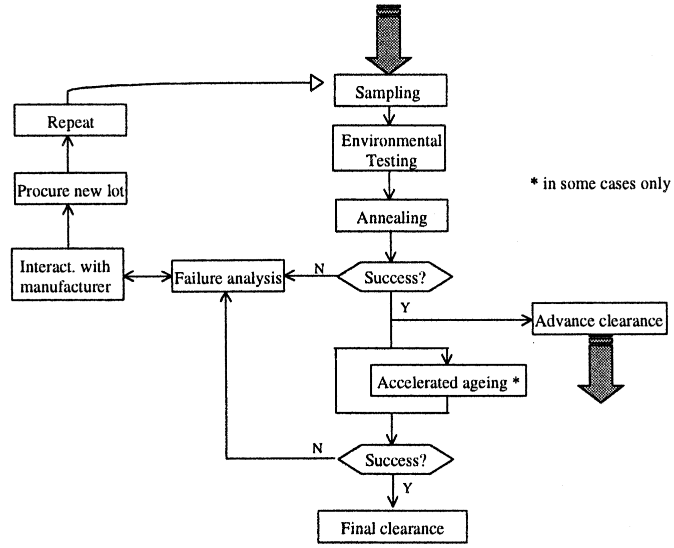

Fig. 8. Flow chart of the AVT procedure for radiation hardness assurance.

In the worst-case position of lasers in the CMS Tracker, the fluence can be equated to 2.3×10^{14} (300 MeV/c) pions/cm^2. We made an assumption that 300-MeV/c pions are equivalent in terms of radiation damage to the entire hadronic flux (excepting the $\sim$ 1-MeV neutron component) within the Tracker. This was justified in that pions with 300-MeV/c momentum (190-MeV kinetic energy) are expected to represent a worst-case because this momentum has the largest peak in the pion–nucleon interaction cross section [19]. A safety factor of 1.5 has also been included to allow for the systematic uncertainties in the radiation environment simulations [2].

The maximum increase in threshold current is 5.3 mA, above an initial value of $\sim$ 4 mA at -10°C [12]. This increase is to be compared with the specified maximum threshold current of 45 mA, which can be compensated by the programmable dc offset at the laser driver ASIC [4].

In conclusion, the lasers therefore qualify as being sufficiently radiation hard. There is also a considerable safety margin remaining that gives good confidence in the final choice of laser for the CMS Tracker optical links.

III. Radiation Hardness Assurance

Despite the very positive results reported here, the laser transmitters are based on COTS parts, and as such, their radiation resistance is not guaranteed. Validation testing must therefore continue throughout the final production of the transmitters to assure that the final optical links will be sufficiently radiation hard. In this section, we present the advance validation test (AVT) procedure that will be followed for the lasers. The primary aim of the laser AVT is to test rapidly a sample set of lasers from a given wafer before a large quantity of transmitters have been assembled using laser die from the same wafer. This should avoid any potential problems and subsequent delays that would be caused by the rejection of a whole batch of fully assembled devices because they were later found to be noncompliant with the Tracker environment.

The AVT procedure is outlined in Fig. 8. The previous qualification testing has, in effect, also validated the methodology, and the AVT procedure is therefore based on a subset of the tests used already for qualification. The first AVT of lasers for final production is scheduled to take place over three months starting in August 2002. This first test will be followed by at least four more identical tests of other candidate laser wafers, which have been scheduled at periodic intervals, just in advance of production, over a two-year period.

From each laser wafer, a sample group of 20 lasers will be irradiated and aged (along with ten unirradiated reference samples) in order to validate a given wafer for radiation resistance. The AVT samples will, as in the earlier qualification tests, be supplied packaged in the final form and burned-in.

The irradiation steps will be made with devices irradiated under bias and at room temperature, using ^{60}Co gamma rays and then 20-MeV (average energy) neutrons, up to doses and fluences equivalent to the worst-case in the Tracker, i.e., $\sim$ 150 kGy and $\sim 5 \times 10^{14} (\sim 20 - \text{MeV neutrons})/\text{cm}^2$. These figures again include a safety factor of 1.5 and include the damage factor of the 20-MeV neutron source relative to 300-MeV/c pions.

In situ monitoring of the laser L-I and V-I characteristics will be done, with measurements made at periodic intervals before, during, and after irradiation, as in the earlier tests. The rates of degradation and annealing of the threshold current and output efficiency can therefore be determined and extrapolated, with the appropriate corrections made to transform the damage to that expected at -10°C inside the CMS Tracker.

The accelerated aging step will be made for as long as time permits, with lasers, both irradiated and unirradiated, being aged at 80°C, and 60 mA. If the available time is too short and no wearout-related changes have been observed already in the unirradiated reference lasers, where the aging can start sooner, then advance clearance may be given to the supplier to begin transmitter production with lasers from the wafers under test.

Acceptance criteria for candidate laser wafers will be such that 95% of the lasers should remain within all the operating specifications for the system, under the worst cases of radiation damage, extrapolated throughout the full ten-year lifetime of the links. Effectively, this means that no more than one laser is allowed to fail the AVT out of the group of 20 irradiated samples and tenunirradiated control samples. This allows for failure of a single component, which could be due, for example, to a random cause, not necessarily relevant to the final application, without leading to rejection of the wafer. Given the large safety margin measured during qualification, very few samples are expected to fail due to the effects of radiation damage or wearout.

Wafers that pass the AVT step successfully will be stored and then used for the production of final devices. In the unlikely event that a sample group of lasers fail the acceptance test, the corresponding wafer will be rejected and a new lot of devices procured from a different wafer.

IV. Discussion

Many questions and issues related to device qualification have been raised during the two-year period taken to carry out the qualification and to define the QA program. In this section, we will discuss some of the most important points.

A. Test Procedures

One of the main issues concerning radiation hardness qualification and assurance was the requirement for a clear definition of the test procedures. It was realized early in the project that we would need to define our own specific validation and qualification test procedures, as opposed to following a standard test-plan, in light of the unique environment inside the CMS Tracker.

The first irradiation tests of lasers for this project were made in 1996, and the procedures then evolved over a two-year period to accommodate the use of different radiation sources and to measure the effects of bias and temperature on the damage and annealing rates. A common feature of the procedures was that the irradiation tests were made with doses or fluences close to, or in excess of, the worst case expected in the Tracker. This method allowed any gross weaknesses to be identified quickly in order to eliminate unsuitable candidate components before much effort had been invested.

B. Number of Devices to Test

The question of the number of devices to test was influenced by several factors, including how many lasers are needed to qualify a batch, or to measure a particular effect, how many lasers could be tested at once, and the resources available for testing and for the purchase of samples.

In discussions with the manufacturers, it was decided that a few tens of devices were sufficient to validate or qualify a whole wafer of several thousand lasers. This can only be the case for devices where the manufacturing process is sufficiently stable and reliable.

Radiation damage is not the only concern and many devices have already been included in the in-system functionality tests. The 28 lasers tested here were aimed specifically at quantifying the radiation damage and annealing (and then wearout) at the level of the laser chip. The transmitter package, in contrast, was already known to be radiation-hard based on earlier studies of a different laser die mounted in a similar package [10].

Several hundred more transmitters will be tested from pre-production deliveries in 2002, of which 120 lasers will have been included in AVTs during the same period. Final mass production of the lasers for the links will only start after successful qualification of the pre-production laser transmitters and successful advance validation of the candidate wafers.

C. Acceptance Criteria

The acceptance criteria for the qualification tests and AVT (and the appropriate failure actions) were defined in consultation with the laser supplier and chip manufacturer. It should be re-emphasized that none of this work could be expected to succeed, particularly the AVT steps, without there being a good relationship and regular contact between CERN and the component manufacturers.

The acceptance criteria are ultimately based on the tolerable level of failure of components within the CMS Tracker. There is only a small amount of redundancy in the Tracker in terms of pattern recognition of tracks from physics events. If the signal-points that make up a track passing through CMS are not reconstructed, then the track might be lost from the analysis. In the large analogue optical link readout system, redundancy is not affordable, and therefore, very few laser failures can be tolerated. This is the basis of the 95% pass-rate in the AVT program, where no more than one device per batch of 30 from a given wafer is allowed to fail.

V. Conclusion

A series of accelerated validation tests have been carried out to qualify the radiation hardness of 1310-nm InGaAsP/InP multi-quantum well lasers for the CMS Tracker optical links project.

The most important effect of the radiation damage was observed to be an increase of the threshold current, which is expected to be related to a decrease in carrier lifetime caused by displacement damage in and around the active volume of the laser. The lasers were only significantly degraded by displacement damage when using test fluences of at least 10^{14} particles/cm^2. Exposure to 100-kGy^{60}Co gamma rays caused no measurable damage. Overall, 300-MeV/c pions were the most damaging particle type used, and the relative damage factors were $\sim 0 : 0.12 : 0.53 : 1$ for ^{60}Co-gamma, 0.8-MeV (average energy) neutrons, 20-MeV (average energy) neutrons with respect to 300-MeV/c pions.

The threshold current damage anneals following irradiation with the recovery being approximately proportional to log(annealing time). The annealing can be accelerated by either increasing the laser bias current or by increasing the temperature of the laser.

Irradiated lasers did not degrade measurably during 2500 h aging at 80°C at 60-mA bias. This suggests that the lifetime of irradiated lasers of this type is well in excess of 10^6 h at -10°C for the levels of radiation damage considered here.

The precise details of the damage and annealing mechanisms are not yet understood. However, the essential features of linear introduction of damage with particle fluence and then the linear annealing with log(annealing time) allowed a robust extrapolation of the experimental data to cover the full lifetime of lasers inside the CMS Tracker. In the worst case, the damage to the laser threshold current is expected to be $\sim$ 6 mA (and the corresponding efficiency loss limited to $\sim 5\%$).

It can be concluded that these lasers successfully qualify, in terms of radiation resistance, for use in the CMS Tracker optical links. There should be a large safety margin in the final application, given the capacity of the laser driver ASIC to compensate the radiation damage effects in the laser.

Because all of the laser transmitters are assembled using COTS parts, some of the validation test procedures used during the development phase will therefore be repeated at intervals throughout the final production phase of the project. An AVT procedure has been specially defined for this purpose, in collaboration with the laser supplier and manufacturer. By pre-testing a set of laser samples from each candidate final wafer, the AVT program will assure the radiation hardness of the lasers used in the final systems.

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