Comparative Study of Radiation Hardness of Optoelectronic Components for the CMS Tracker Optical Links§

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Abstract

Commercially available semiconductor lasers and p-i-n photodiodes from several different manufacturers have been irradiated with 6MeV neutrons to fluences up to 10^{15}n/cm^2. A comparison of the radiation damage in the lasers is made in terms of the threshold current increase and efficiency loss. In the irradiated p-i-n photodiodes, the damage to leakage current and responsivity is compared. The laser damage was similar overall after normalising the changes with respect to the pre-irradiation values. The p-i-n photodiodes had similar leakage current increases overall. The detectors that were front-illuminated are more radiation resistant than the back-illuminated devices in terms of the photocurrent damage.

I. INTRODUCTION

Optical links will be used extensively in experiments at the Large Hadron Collider (LHC) due to their advantages of large bandwidth, low power requirements, compactness and noise immunity in comparison to copper cables. An analogue optical link system is being developed[1] at CERN for readout of the Compact Muon Solenoid (CMS) tracking detectors, in addition to a digital link system for transmission of timing, trigger and control signals. Approximately 50000 analogue and roughly 1000 digital fibre channels will be required in total.

By using components already available in the telecommunications market, special custom development can be avoided and the large number of optical links can be constructed on a limited budget. However, all the candidate components have to be tested for sufficient radiation hardness as the radiation environment in the CMS tracker will be severe: total particle fluences over the first 10 year running period will be up to ~10^{14}neutrons/cm^2 (~1MeV), 1.6x10^{14} charged hadrons/cm^2 (mainly charged pions, ~10^2-10^4MeV), in addition to an ionising dose of up to 70kGy[2].

For the analogue readout links, and the digital links carrying signals from the tracker, the laser transmitters, optical fibres and connectors will be exposed to high radiation fluences. In the digital links, sending timing and control signals to the tracker, p-i-n photodiode receivers will also be placed in the radiation field. We have already extensively tested[3] NEC lasers and Epitaxx p-i-n diodes packaged by Italtel[4] and are confident that these particular components are sufficiently radiation resistant for use inside the CMS tracker. For the fluence/dose levels of interest, ionising damage (from ^{60}Co gamma rays) was determined to be insignificant compared to the effects of displacement damage from 6MeV neutrons, 300MeV pions and 24GeV protons, whose relative damage ratios have been determined[3]. In this study we aim to determine if the levels of 6MeV neutron damage are similar in candidate CMS optical link components from a range of manufacturers.

II. EXPERIMENT

Lasers from 6 manufacturers were tested as well as p-i-n photodiodes from 6 manufacturers. All the components are potentially suitable, in terms of performance and packaging, for use in the CMS tracker optical links. The type and number of each device is summarised in Table 1. All the devices are based on commercially available components, some obtained directly from the manufacturer and others, such as the NEC and Mitsubishi laser die, and the back-illuminated Epitaxx p-i-n photodiodes were supplied in packages by Italtel.

Table 1: Lasers and p-i-n photodiodes irradiated in this study which includes three separate neutron irradiation tests (A, B and C).

Laser Manufacturer	NEC (Italtel)	Alcatel	Lucent	Nortel	Mitsubishi (Italtel)	Optobahn
Type	1310nm, multi-quantum-well, edge-emitter					
Die	1-way					8-way
Package	custom 4-way DIL, SM fibre ribbon	TO-can SM-fibre pigtail	mini-DIL SM-fibre pigtail		TO can, no fibre	40-pin chip, 8-way MPO socket
No. irradiated (Test)	1 (B)	2 (A)	2 (A)	2 (B)	5 (A)	1 (B)

P-i-n Manufacturer	Alcatel	Nortel	Epitaxx	Fermionics	Lucent	Epitaxx (Italtel)
Type	InGaAs/InP planar p-i-n structure					
p-i-n diameter	n/a	n/a	75µm	80µm	75µm	
Orientation	Front-illuminated				Back-illuminated	
Package	TO-can, SM-fibre			ceramic submount, SM fibre		mini-DIL SM-fibre
No. irradiated (Test)	3 (A)	3 (A)	3 (B)	2 (A) + 6 (B)	2 (A)	5 (C)

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Irradiation was carried out at the SARA neutron irradiation facility[5]. Neutrons with a mean energy of 6MeV are produced by bombarding a beryllium target with a 18MeV deuteron beam. As shown in Table 2, particle fluxes of up to ~$4x10^9$n/cm^2/s were used to expose the device samples to total fluences between $3x10^{14}$n/cm^2 and $1.2x10^{15}$n/cm^2. Nickel dosimetry foils were placed on each irradiated device and the fluences are accurate to ~10%. Note that the neutron fluences are higher than the fluences expected inside the CMS tracker. This allows us to predict the damage from the other important types of particle in the tracker, e.g. 300MeV pions, which are more damaging than 6MeV neutrons[3]. In addition (but outside the scope of this report) Test A was split into 3 steps in order to study the effect of annealing in more detail.

Table 2: Parameters of the different neutron irradiation tests.

Test (date)	A (11/97)	B (5/98)	C (11/96)
No. exposures	3	1	1
Irradiation (I) and recovery (R) duration (hours)	59.3 (I) + 82.4 (R) + 58.8 (I) + 110.6 (R) + 51.5 (I) + 260 (R)	97.3 (I) + 330 (R)	102 (I) + 2100 (R)
Flux range over irradiated devices (10^9n/cm^2/s)	0.5 to 2.0	1.2 to 3.8	1.0 to 2.7

The light-power versus current (L-I) and voltage versus current (V-I) characteristics of the lasers were measured in-situ at 30-40 minute intervals during irradiation. The threshold current and slope-efficiency were determined by fitting a line to the linear region of the L-I characteristic. For the Mitsubishi devices, that were packaged in TO-cans without fibre pigtails, the threshold current was determined from the position of the characteristic kink in the V-I curve that occurs at the laser threshold.

The photodiodes were illuminated using a temperature-stabilised 1310nm laser situated outside the irradiation zone. The leakage current and photocurrent (for optical power levels between 0 and 300μW) were measured during irradiation, at five different reverse bias voltages: 0V, 2.5V, 5V, 7.5V and 10V. The photocurrent was measured by monitoring the p-i-n current whilst ramping the current through the external laser. Another p-i-n diode, outside the irradiation cell, was used to monitor any fluctuations in the laser power output.

Irradiation was done at ambient temperature, 18-20°C, with the devices kept under electrical bias (lasers at 5-10mA above threshold, and p-i-n photodiodes at -5V) in the idle period between measurement cycles.

III. RESULTS

A) Lasers

A comparison of the radiation induced degradation of the laser thresholds and efficiencies, normalised to the pre-irradiation values, is shown in Figs. 1 and 2. In terms of device performance, the threshold current is degraded much more than the efficiency, relative to the initial values.

Across the range of manufacturers, the damage effects are found to be similar overall to within a factor 2. For the threshold damage, the NEC and Lucent lasers have the smallest relative increase and the Optobahn devices have the smallest absolute increase. The output efficiency is also less affected in the NEC and Lucent devices. The efficiency data for 4 channels of the Optobahn lasers were too noisy, due to non-linearities in the L-I data, to be significant and have been omitted from Fig. 2.

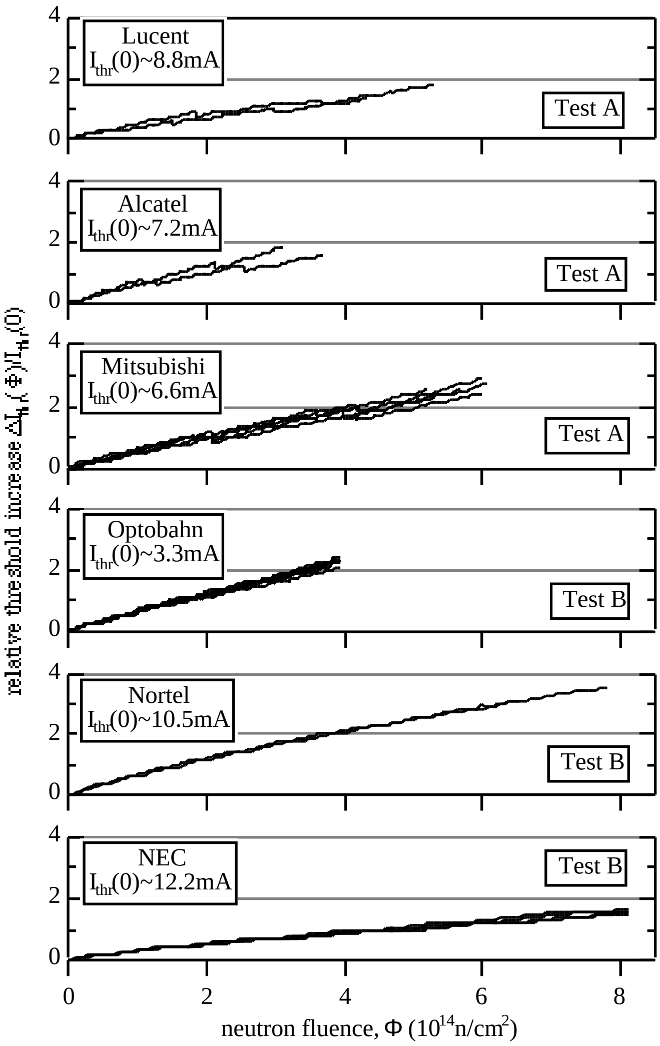

Fig. 1: Comparison of threshold current increases during 6MeV neutron irradiation in lasers from several manufacturers.

The discontinuities visible in the damage data for devices in Test A are due to the gaps between the three separate irradiation steps (see Table 2). During these periods some annealing occurred (~14-23% after the first step and 11-17% after the second step). No corrections have been applied to the data to compensate this effect, as it is fairly small and the annealing kinetics are not sufficiently well understood to apply an accurate correction. Overall, the amount of damage is lower in the Test A samples at a given fluence, compared to the expected level of damage if the same samples were irradiated under Test B conditions. A further experiment is planned to study the annealing behaviour in more detail in order to make better comparisons of devices irradiated under different conditions.

The increase in laser threshold and the efficiency loss are both consistent with the effects of displacement damage, normally explained in terms of the recombination lifetimes of injected charge carriers. Radiation damage causes the carrier lifetime associated with non-radiative recombination at defects to eventually decrease to a level similar to the lifetime associated with spontaneous recombination[6]. The resulting competition between these two processes causes the increase of the threshold current. Above threshold however, the stimulated recombination lifetime is much shorter than the lifetime associated with non-radiative recombination at defects and the laser efficiency is less affected by displacement damage (at least until high fluences are reached ~$10^{14\text{-}15}$n/cm^2).

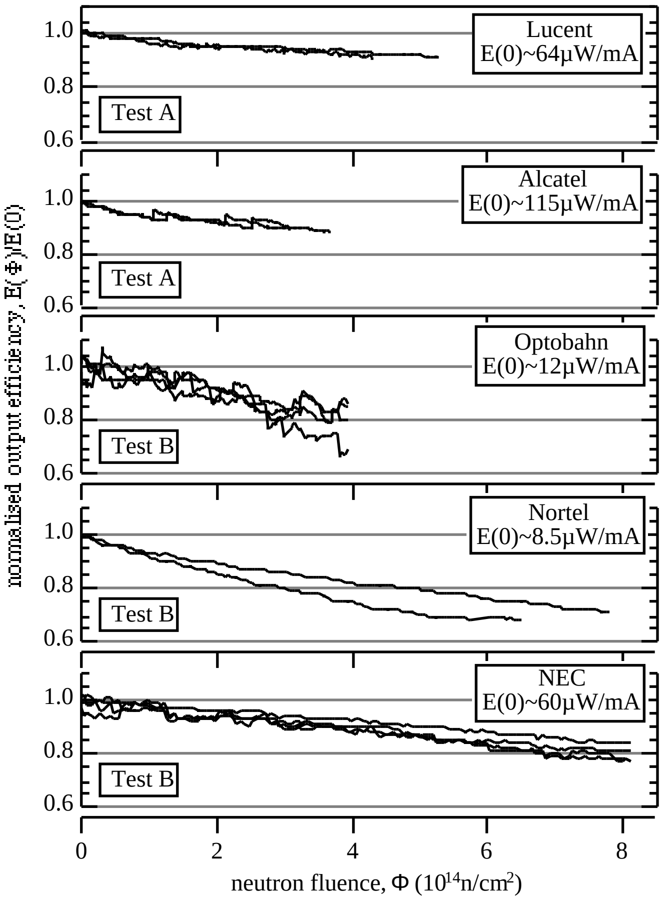

Fig. 2: Comparison of output efficiency degradation during 6MeV neutron irradiation in lasers from several manufacturers.

B) P-i-n photodiodes

The damage effects observed in the p-i-n photodiodes included a large increase in leakage current and a decrease in the responsivity. These effects are both consistent with the expected build-up of radiation induced defects in the bulk leading to the generation of dark current and the trapping/recombination of signal charge[7,8]. Both of these damage effects were generally non-linear with increasing fluence. This would normally make a comparison of several devices very difficult to perform but, as very little annealing occurred after irradiation, the results can therefore be compared directly in terms of the damage after a given neutron fluence.

Fig. 3 shows the leakage current damage (at 5V reverse bias) in all the irradiated devices. The radiation induced leakage current increases to more than 6 orders of magnitude greater than typical pre-irradiation values of ~10pA at -5V and, overall, the increases are similar for all the different devices.

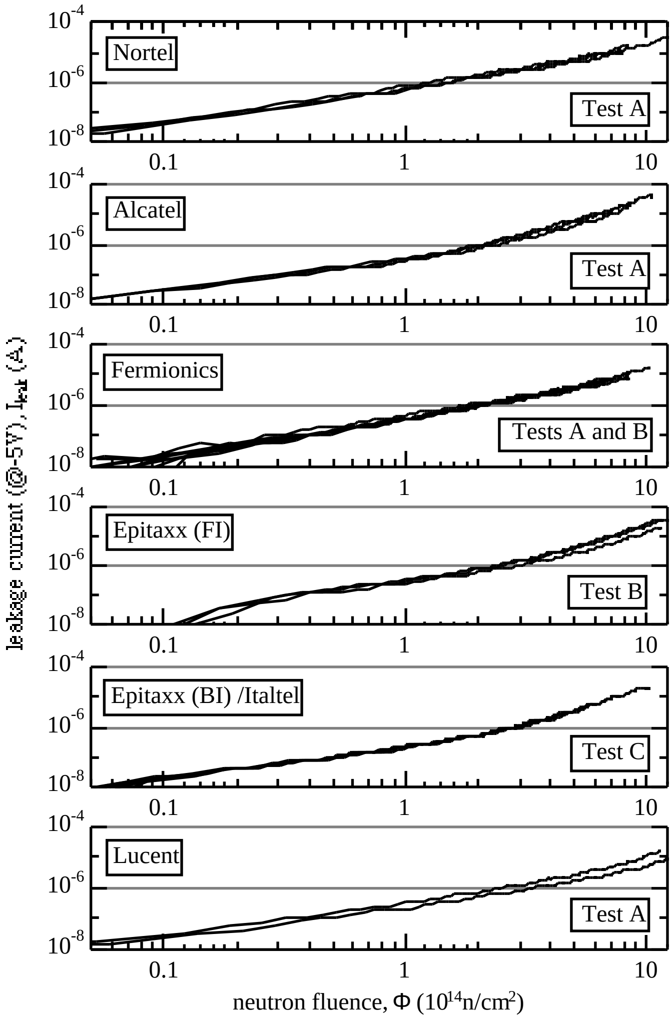

Fig. 3: Comparison of p-i-n leakage current increases during 6MeV neutron irradiation in devices from several manufacturers.

The effect of neutron damage on the p-i-n responsivity is illustrated in Fig. 4, showing the photocurrent at -5V bias for a ~200μW d.c. optical signal, normalised to the pre-irradiation value. The pre-irradiation responsivity was typically 0.9A/W for all the devices. Three distinct types of radiation damage effect occurred: (i) a rapid decrease in response after a certain fluence (Epitaxx/Italtel and Lucent, both back-illuminated), (ii) a more linear and smaller decrease (Epitaxx TO and Alcatel, both front-illuminated) and (iii) a mixture of both degradation and recovery during irradiation (Nortel and Fermionics, both front-illuminated).

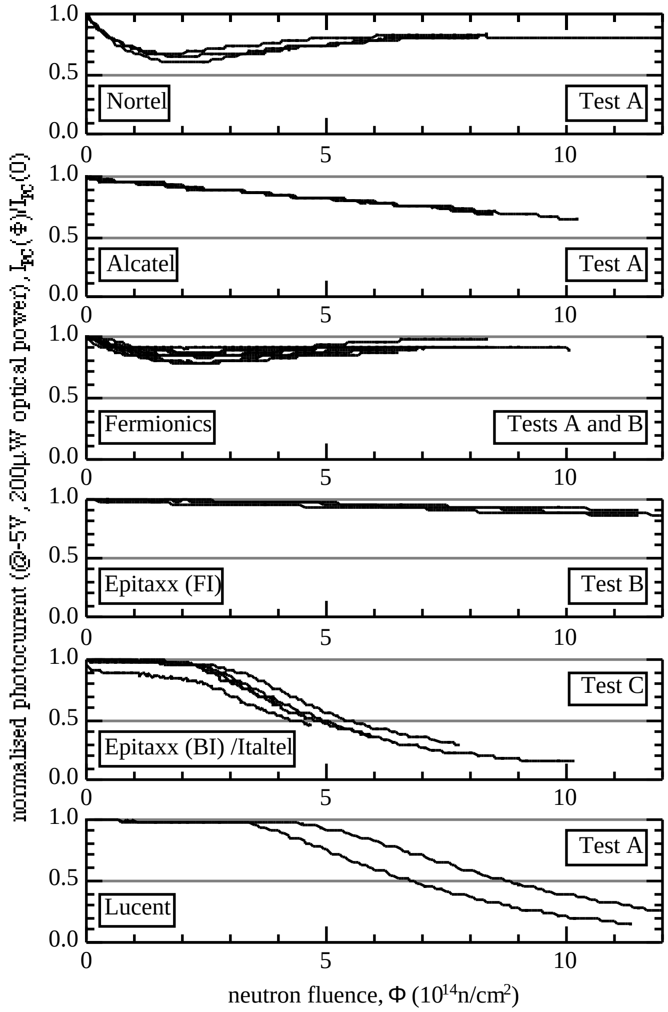

Fig. 4: Decrease in normalised photocurrent at -5V for 200µW optical signal during 6MeV neutron irradiation

Although the mechanisms of the different damage kinetics are not yet understood, it is clear that the front-illuminated devices appear to be more radiation resistant than the back-illuminated devices in terms of the responsivity change. In the case of the two types of Epitaxx devices tested, the p-i-n structures are identical except for the direction of the incident light. The reason for the difference in the radiation damage could be due, for instance, to the effects of introducing mainly acceptor-type defects into the InGaAs layer. After a sufficiently high fluence the low level of initial n-type doping in the InGaAs layer would become fully compensated by the negatively charged defects, which are then expected to be effective trapping centers for signal induced holes. Due to the short optical absorption length of InGaAs at 1.3µm, this situation would be more damaging in back-illuminated p-i-n diodes than in front-illuminated devices because signal induced holes must travel a greater distance through the InGaAs layer in a back-illuminated detector.

IV. SUMMARY

We have found that a variety of commercial 1310nm lasers and InGaAs p-i-n photodiodes should meet the stringent radiation hardness requirements for operation in the CMS tracker over a 10 year period.

The damage effects in the irradiated lasers were relatively similar overall; e.g. after $4x10^{14}$n/cm^2 (approximately the highest fluence common to all the types of devices tested), the threshold current increase was 100-200%, relative to the initial value, and the output efficiency was degraded by between 10% and 25%. The p-i-n photodiode leakage current damage was also similar across the range of devices, with ~10µA leakage at -5V after 10^{15}n/cm^2. For neutron fluences in excess of ~$2x10^{14}$n/cm^2, the front-illuminated p-i-n photodiodes were more radiation resistant, in terms of photocurrent damage, with only 10-35% signal loss after 10^{15}n/cm^2, compared to 60-90% degradation in the back-illuminated devices.

V. ACKNOWLEDGMENTS

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VI. REFERENCES

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