Neutron damage studies of semiconductor lasers for the CMS tracker optical data links

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abstract

The raw data from the silicon and MSGC tracking detectors in the future CMS Experiment at the LHC will be acquired via a 60000 channel, 100m long, analogue optical link. The use of directly modulated lasers is being investigated as a possible solution for the CMS optical link. Prototype lasers and monolithic laser arrays have been obtained from several manufacturers and the issues to be investigated include device performance, radiation hardness, reliability, packaging and projected cost. The test of radiation hardness precludes further investigations therefore this paper focuses on the performance of lasers and laser arrays before, during, and after irradiation with 6MeV neutrons.

1. INTRODUCTION

Analogue optical links are currently being developed at CERN to read out the data from the 10^7 microstrip channels of the CMS tracker. The raw data will be multiplexed at 256:1 and then transmitted at 40MHz along the 60000 channel, 100m long link. The extreme environment of the inner tracking volume dictates that optical link elements inside the tracker volume must be radiation hard to at least 20Mrad and the equivalent of $\sim 10^{14}$neutrons.cm^{-2}.

This paper focuses on the possible use of directly modulated lasers, or monolithic laser arrays, as the transmitters for the CMS optical links. Recent developments have brought low threshold, high power, high reliability, ultra-compact lasers and laser arrays into the marketplace. An initial assessment of these devices must include an investigation of the effects of radiation damage. This is fundamental to their long term operation within the CMS inner tracker and it precludes further investigation of a laser based link.

2. EXPERIMENT

2.1 DEVICES STUDIED

Around 100 lasers of four different wavelengths, from several manufacturers, have been measured to date. The different types of laser considered in this particular study are shown in Table 1. All of the devices tested were based on quantum-well (QW) structures, which act to confine the injected electrons and holes. Population inversion is subsequently reached with a lower threshold current than in conventional solid state lasers[1].

laser type	A	B	C	D
wavelength (nm)	850	980	1300	1300
QW structure	multi	single	multi	multi
emitter type	VCSEL	edge	edge	edge
No. lasers/die (pitch in µm)	5 (250)	1	12 (250)	1
No. tested	10x5	8	2x12	5

Table 1: Laser types tested.

2.2. NEUTRON IRRADIATION

A number of the different lasers were irradiated with 6MeV neutrons at the SARA facility[2] in Grenoble, France. The experimental arrangement is shown schematically in figure 1. Four devices of each type were biased and monitored at regular intervals before, during, and after the irradiation period.

Of the type B lasers, two had been previously irradiated with ^{60}Co photons to ~12Mrad. This was found to have little effect on the device performance. The neutron fluence was measured by activated foil dosimetry to be 1.1×10^{14}n/cm^2 (±15%) at the lasers and estimated to be less than 10^{11}n/cm^2 at the monitoring photodiodes. The dose rate was approximately constant over a period of 43 hours and the irradiation cell was at room temperature. The temperature was monitored but not controlled. The devices were monitored for a total period of around 300 hours with the irradiation occurring in the 64 to 107 hour interval.

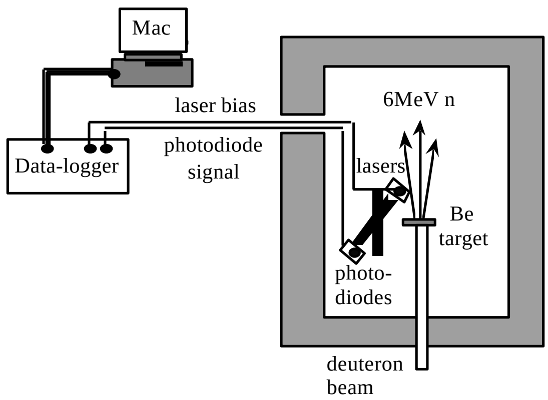


Fig. 1: Schematic experimental arrangement for the neutron irradiation.

3. RESULTS

3.1 PRE-IRRADIATION MEASUREMENTS

The light power versus input current (L-I curve) characteristics were measured for each laser type. Typical L-I curves for each type are shown in figure 2. The L-I measurement forms the basis of the subsequent determination of laser threshold current, efficiency (ratio of output power to input current) and output linearity.

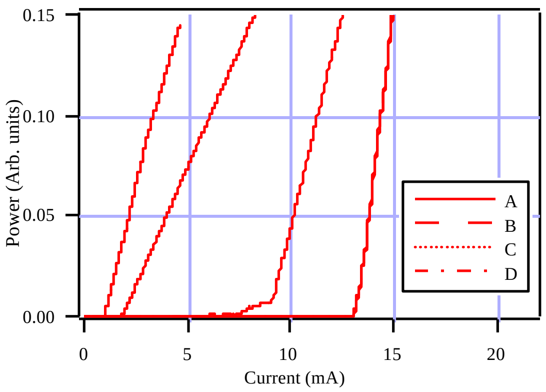


Fig 2: Typical L-I curves for the four laser types.

The L-I curves were measured by monitoring the output of a photodiode placed in front of the laser. By using a large enough photodiode, typically 5mm diameter, it was possible to collect all of the laser light, which is emitted in a cone (elliptical cross section for edge-emitters, circular for VCSEL) with a FWHM divergence of up to ~30°. A saw-tooth current waveform was used to drive the laser, with a frequency of ~1Hz. The amplitude was set to suit the particular laser type; devices of type A were ramped to ~8mA, B to ~40mA, C to ~15mA and D to ~40mA. An average was made of 100 measurements before storing the data.

Using a small InGaAs photodiode (diameter 300µm), the signal to noise ratio (S/N) in a 10Hz-30MHz bandwidth was also measured. Results for type D lasers are shown in figure 3. For a given input DC current, S/N was determined from the DC output level divided by the root-mean-square of the AC-coupled output level. The noise contribution of the photodiode and amplifier was subtracted using the measurements made below the threshold current.

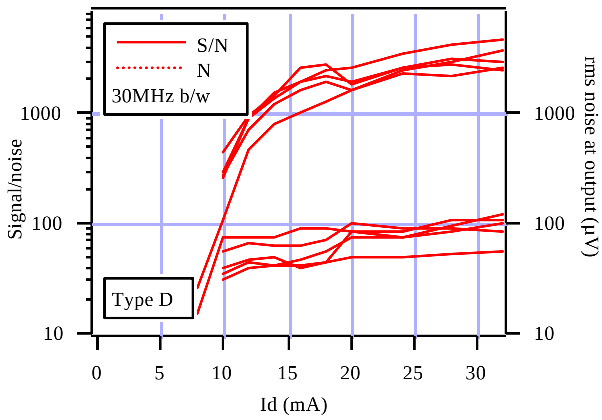


Fig. 3: S/N measurements for type D lasers.

3.2 MEASUREMENTS DURING IRRADIATION

The transfer characteristics were measured at intervals of 35 minutes. Some results for type C lasers are shown in figure 4. Three effects of the irradiation are immediately apparent: the increase in threshold current, the decrease in efficiency, and the increase in the leakage current in the photodiode.

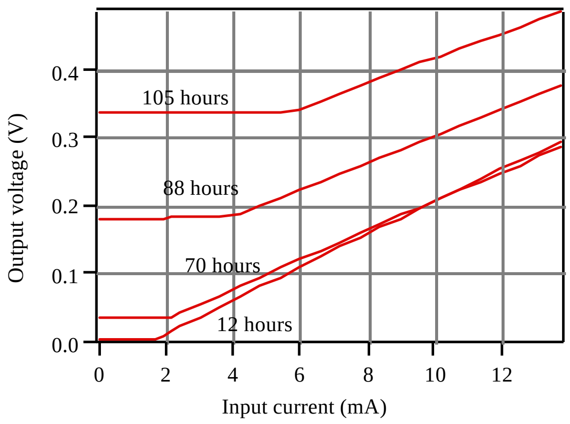


Fig. 4: Sample of results for type C lasers measured during the irradiation test. Irradiation took place between 64 and 107 hours.

After subtracting the increases in leakage current in the monitoring photodiodes, the threshold and efficiency was calculated. Figure 5 shows how the threshold varied with time for the Type D lasers. The linear increase of threshold with fluence during irradiation, followed by some annealing, was observed for all of the laser types. The threshold currents are slightly higher in this figure than the true values since the threshold was defined as the current at which the output reached a particular level. This approach was necessary as insufficient points were measured on the transfer characteristic to extract the threshold value by the usual method of determining the peak in the second derivative.

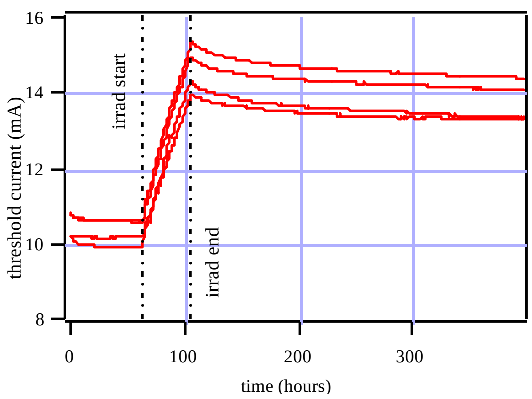


Fig. 5: Change in the laser threshold current for type D lasers.

The efficiency data is illustrated in figure 6 for type D lasers. At this time it was not possible to separate the actual effect of laser efficiency loss from the possible degradation of the monitoring photodiode due to radiation damage. Later measurements in the lab (see section 3.3) confirmed that the apparent losses were indeed due to radiation damage effects in the photodiodes.

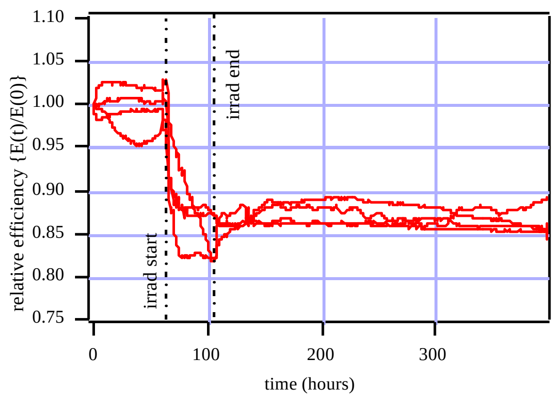


Fig. 6: Change in the laser efficiency for type D lasers.

3.3 MEASUREMENTS AFTER IRRADIATION

The L-I curves were remeasured in the laboratory, between two and four weeks after irradiation. The results are compared with typical pre-irradiation curves in figure 7. The threshold was determined by finding the peak in the second derivative in the L-I curve and Table 2 illustrates the measured values before and after irradiation.

laser type	A	B	C	D
mean I_{thr} (mA) (pre-irrad)	0.95	14.7	1.8	9.1
mean I_{thr} (mA) (post-irrad in lab)	1.09	23.4	5.4	11.7

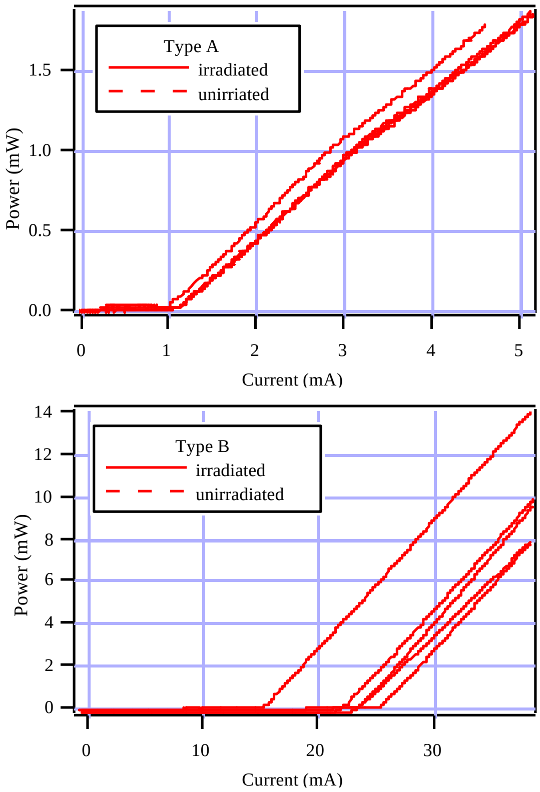
Table 2: Threshold measurements before and after irradiation.

The efficiency was determined from the slope of a line fitted to the data above threshold. A 5mm diameter germanium photodiode was used to measure the 1300nm lasers (C and D), ensuring full light collection. Comparison with the manufacturers' data sheets allowed the efficiency to be related to the pre-irradiation values. Lasers A and B were measured with the same 100mm^2 silicon photodiode used before irradiation therefore a direct comparison with the pre-irradiation L-I curves was possible. Table 3 shows the results of the efficiency measurements compared before and after irradiation. The laser efficiency was therefore determined to be relatively unaffected by radiation damage. Only in the type B lasers was there any significant change after neutron damage and this was at a low level of ~10-20%.

laser type	A	B	C	D
mean E (W/A) (pre-irrad)	0.52	0.51	0.39	0.50
mean E (W/A) (post-irrad in lab)	0.48	0.44	0.38	0.51

Table 3: Efficiency measurements before and after irradiation.

A measurement of the signal to noise ratio was also made for each irradiated laser and figure 8 illustrates the results after irradiation for type D lasers. There was no significant degradation in S/N performance relative to the pre-irradiation data; this was the case for all the laser types.



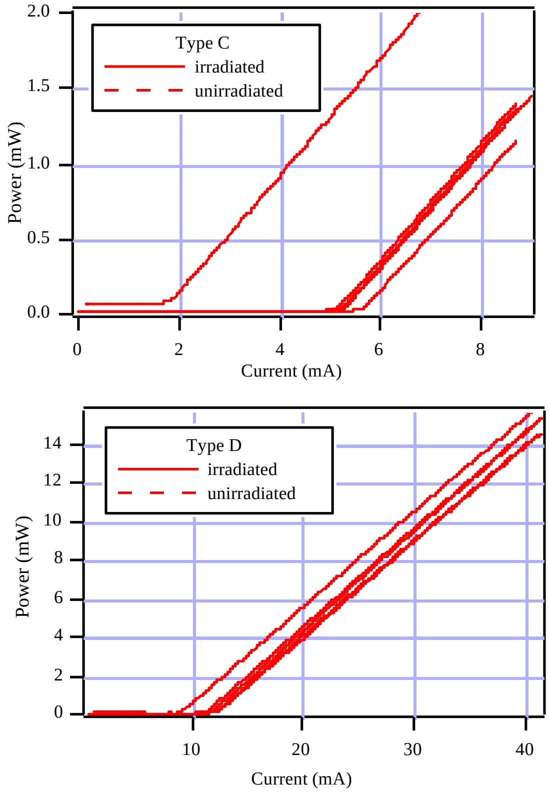


Fig. 7: L-I curves measured in the lab after irradiation.

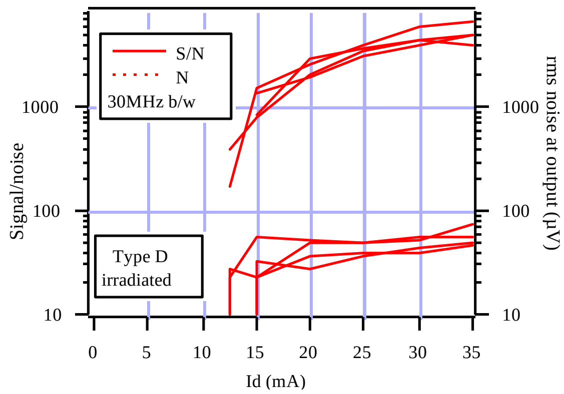


Fig. 8: S/N measurements for type D lasers after irradiation.

The deviation from linearity was also determined by fitting a second line to the data, based on the laser being operated at some DC bias point, in this case a value of 10% above threshold. The deviation from linearity, D (in %), was defined as,

$$D = \frac{100 \times (y_{fit} - y_{data})}{(y_{fit} - y_{dc})}$$

where y_{dc} is the laser output at the DC bias point. Figure 9 illustrates the results for lasers of Type D.

Again there was no significant degradation due to radiation damage.

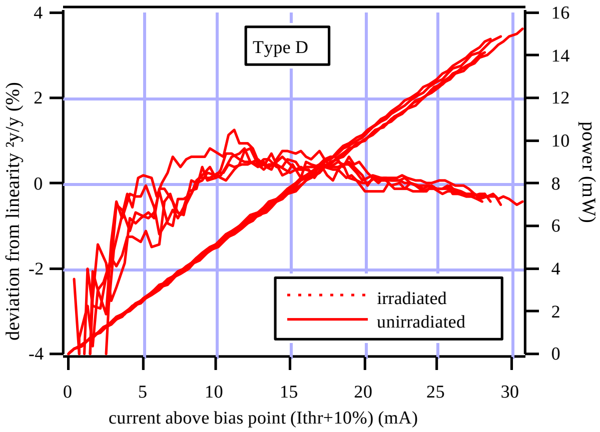


Fig. 9: Linearity measurements for type D lasers.

4. DISCUSSION

Reliability data exists for unirradiated laser of types B, C and D with typical figures being 100 FITS for type B lasers and 1000 FITS for types C and D, where 1 FIT is 1 failure in 10^9 device-hours [3]. For irradiated devices there is no data for reliability and it is clearly impractical to determine lifetimes with a small number of devices. However, if a model of the radiation damage effects can be developed then it may be possible to determine whether the factors that determine the device lifetime are susceptible to radiation damage.

Since all the types of laser appeared to be damaged in a similar way, and since ionisation damage from a previous gamma irradiation had little effect on the type B lasers[4], the observed effects may be due to displacement damage in the bulk of the device. Bulk damage can introduce energy levels into the band-gap [5]; in lasers this would provide non-lasing recombination centres for the injected electrons and holes, illustrated schematically in figure 10.

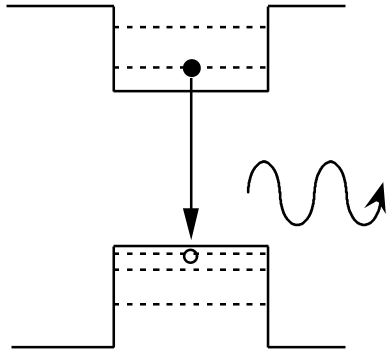


Fig. 10(a): Unirradiated QW laser.

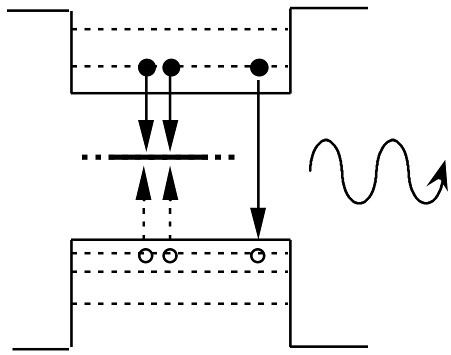


Fig. 10(b): Irradiated QW laser. Recombination competes with lasing transitions.

The observed shifts in threshold current are consistent with the effects of recombination states. The loss of charge carriers due to recombination has to be compensated before lasing can occur, therefore the threshold is increased. This can be pictured overall as a net downward shift of the L-I curve. For a given current above threshold, the laser should then operate at the same intensity as before irradiation, therefore the efficiency should be unaffected. However, if the damage in the QW region is extensive then the laser efficiency may also be degraded.

5. SUMMARY AND CONCLUSIONS

MQW lasers from several manufacturers have been characterised and irradiated as a primary test of whether an optical link based on directly modulated lasers is feasible in the CMS Inner Tracker. 16 lasers were monitored during irradiation with 6MeV neutrons up to a total fluence of $1.1 \times 10^{14} cm^{-2}$.

Threshold currents were observed to increase for all the lasers, with the magnitude dependent upon the different laser type. The efficiency was not significantly affected except for the type B lasers, where a decrease of around 10-20% was observed. The signal to noise ratio was also found to be relatively unaffected by neutron damage. The apparently large efficiency losses observed during the irradiation were found to be due to radiation damage in the monitoring photodiodes.

The radiation damage effects are consistent with the introduction of defect states in the laser substrate, which provide non-lasing recombination centres for the injected electrons and holes. This might not be the only consequence of radiation damage and further effects may also require consideration in order to understand how laser reliability is affected by radiation damage.

Overall, the results of this investigation have demonstrated that several different types of laser are feasible, in terms of their radiation hardness, for use in optical links within CMS. Similar tests are planned using fully packaged, fibre-pigtailed devices, as well as further investigations of lasers from other manufacturers. Other criteria such as projected cost, availability and reliability will now have to be analysed to decide in favour of a particular laser type.

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