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Radiation hardness of the 1550 nm edge emitting laser for the optical links of the CDF silicon tracker

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Abstract

Radiation hardness is investigated for the laser transmitter of the optical links used for the CDF Run II silicon tracker. Beam tests were conducted with 30, 63, and 200 MeV protons with radiation doses up to 2 Mrad. The laser transmitter consists of an edge-emitting-type laser diode array and a BiCMOS driver chip. The laser light degradation is approximately linear to the radiation dose. The light degradation is about 10% at 200 krad. The radiation tolerance is expected to suffice for the CDF Run II operation.

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Optical links are used in the CDF Run II silicon tracker [1] for data transmission out of the detector tracking volume. The transmitter modules are mounted on the front-end port cards [2] on a cylindrical support tube at a distance of 15 cm from the beam axis. A port card has five laser transmitters for silicon ladders configured in a wedge. Each module provides a byte-wide data transmission at 53 Mbyte/s for a silicon ladder. The laser transmitters are connected to 22 m fiber ribbon cables to receiver modules outside the CDF detector. In total, 556 modules were implemented for the CDF silicon tracker readout.

The laser transmitter consists of an 1550 nm edge-emitting-type laser diode array and an ASIC driver [3,4]. The laser diode array is a 12-channel InGaAsP/InP device at 250 μm pitch fabricated by the Chunghwa Telecom [5]. The driver chips were fabricated by the AMS 0.8 μm BiCMOS process [6] using bipolar transistors for high-speed capability and good radiation tolerance. The wafer implantation of the laser diode and the driver circuits are shown in Fig. 1.

The electric signal inputs to the transmitter driver chip are in LVDS or ECL format with a common level around half the chip bias voltage

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(V_{cc} at $+5$ V). The laser diodes are connected to switching circuits terminated with a common voltage level V_{LD}. The laser current is proportional to the voltage drop ($V_{cc} - V_{LD}$) adjusted by the V_{LD} at the level of 2 mA per 0.1 V. The nominal operation current for a laser channel is 20 mA. The power dissipation per module is about 2 W. Light output measured on a bare die at room temperature is about 1 mW.

The module assembly contains a short optical fiber pigtail aligned to the laser facets for light collection. The output end is terminated with a standard MT type connector. The type of fiber used for pigtails and cables is a germanium-doped graded-index multimode fiber of Plasma Optical Fibre [7] known for good radiation tolerance [8].

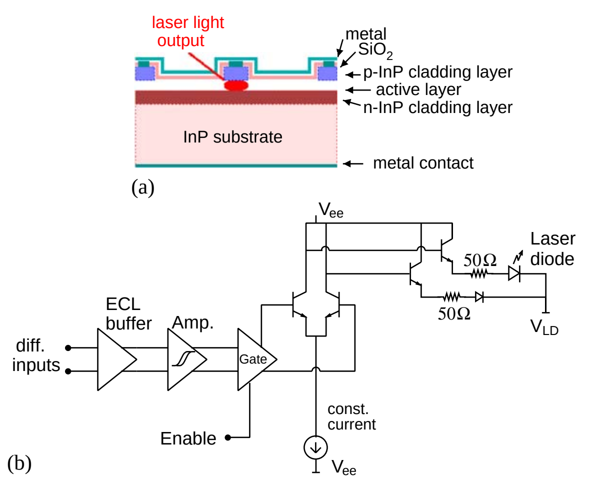

Fig. 1. (a) Wafer implantation of the edge-emitting type laser diode; (b) the laser driver circuits.

Characteristics of the laser transmitter were investigated with the laser light measured by optical-to-electrical (O/E) probes. The light output is sensitive to the laser temperature. The measurements made at three temperatures are plotted in Fig. 2a. The light waveform was examined and compared to the ECL input signals at 50% duty cycle. The laser light has a quick response in duty cycle (Fig. 2b) at the laser turn-on threshold (~ 10 mA) to the required operation range of 50 ± 10%. The light power dependence on temperature is approximately linear. It is shown in Fig. 2c for a laser module operated on a water chilled metal plate in a steady cooling and warming process. The laser light power reduces by about 2.5% per degree increase in temperature.

The laser transmitters implemented inside the CDF tracking volume are required for a radiation tolerance of 200 krad without data transmission error. The dominant radiation damage to the laser transmitters is caused by the particles produced in proton–antiproton collisions in a broad momentum range. The radiation level in the CDF tracking volume has been measured with thermoluminescence dosimeters (TLD) [9] installed on the support tube for the silicon detector. The radiation

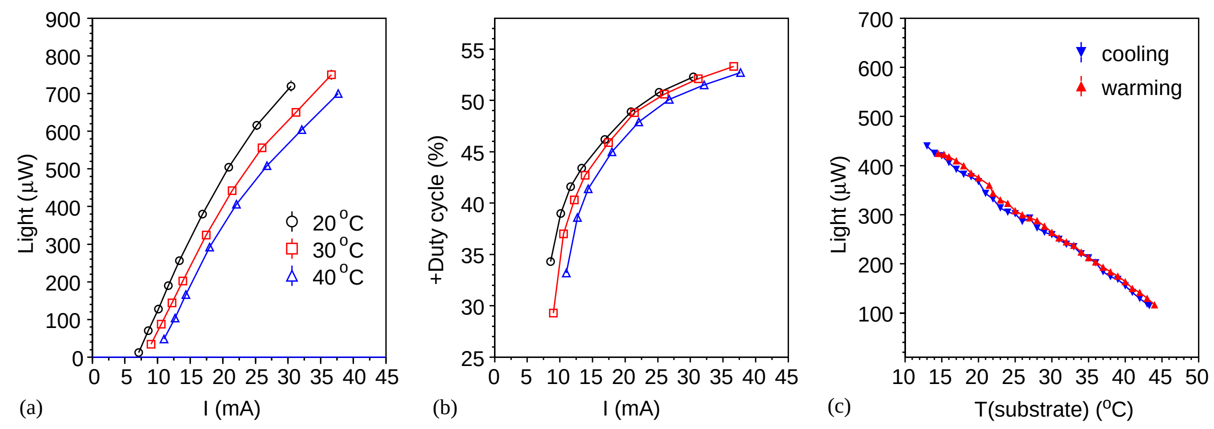

Fig. 2. Measurements of (a) light output and (b) duty cycle versus laser current for a laser diode channel. The temperature dependence for light output is shown in (c).

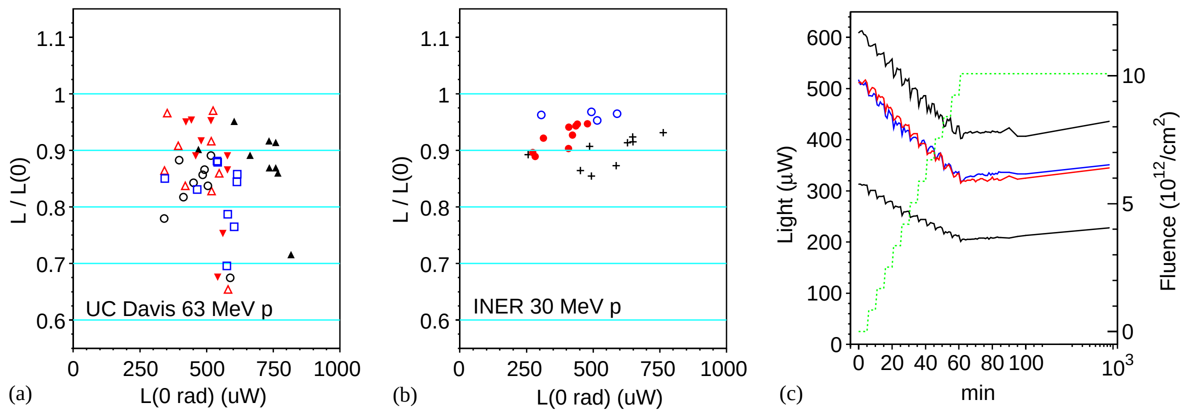

Fig. 3. Ratio of laser light power versus the original after irradiation of 200 krad (GaAs) of (a) 63 MeV and (b) 30 MeV protons, corresponding to a total fluence of 1.9×10^{12} and 1.1×10^{12} p/cm^2, respectively. Channels of a transmitter are labeled by the same mark. Shown in (c) are the light outputs in time of a transmitter irradiated with 30 MeV protons up to 1.8 Mrad (GaAs) (10×10^{12} p/cm^2); the cumulative fluence is illustrated by the dashed line.

field in CDF is described by a power law $D = A/r^{\alpha}$, where r is the distance from the beam axis. The dose rate received by the laser transmitters is estimated to be 17 rad/pb^{-1} corresponding to a fluence rate of 6.6×10^8 MIPs/cm^2 pb^{-1}, where $\alpha = 1.5$ and the TLD conversion factor of 1 rad = 3.87×10^7 MIPs/cm^2 are applied.

The radiation damage in the laser transmitter is predominantly caused by non-ionizing energy loss (NIEL) that results in light power degradation. The radiation tolerance of the laser transmitters was evaluated with 63 MeV protons at the Crocker Nuclear Laboratory at UC Davis. The proton beam was delivered at a dose rate of 0.44 krad/s (GaAs) (4.2×10^9 p/cm^2 s).[1] The laser transmitters, as integrated components on a port card, were biased in air cooled operation condition. The irradiation was performed with a total dose of 200 krad (GaAs) corresponding to a fluence of 1.9×10^{12} p/cm^2 (13×10^{12} 1 MeV n/cm^2).[2] The laser light outputs were measured at room temperature after irradiation and the distribution of light degradation is shown in Fig. 3a. The average laser light output reduced to $87 \pm 8\%$ of the original.

Irradiation tests were also conducted with a 30 MeV proton beam at the Institute of Nuclear Energy Research (INER) in Taiwan. The laser transmitters were mounted on thermo-electric coolers and the laser diodes were biased in DC mode at a constant current of 20 mA each. The transmitters were kept at a stable room temperature around 30 °C. The laser light outputs were connected to a fiber ribbon cable out of the test area. The light power measurements were conducted with optical power meters to a precision of better than 2%. The distribution of light degradation at 200 krad (GaAs), corresponding to a total fluence of 1.1×10^{12} p/cm^2 (8×10^{12} 1 MeV n/cm^2), is shown in Fig. 3b. The average is $92 \pm 3\%$ of the original.

The light degradation is approximately linear to the irradiation dose. The measurements performed with optical power meters at INER are shown in Fig. 3c for four laser channels of a transmitter. The proton beam was delivered in 12 cycles of beam off/on at a dose rate of 150 krad/min (GaAs) (0.83×10^{12} p/cm^2) in the first minute every five mins. The thermo-electric cooler provided a stable heat-bath and the temperature was measured at a precision of 0.1 °C. The proton beam was intense enough to heat up the test device. After the beam

[1]Conversion of fluence to dose equivalent (GaAs) for 30, 63 and 200 MeV protons are 1×10^9/cm^2 = 186, 104 and 47 rad, respectively.

[2]The expected NIEL values (GaAs) for 30, 63 and 200 MeV protons are 4.0, 3.6 and 3.9 keV/cm^2 g, respectively; the NIEL value for 1 MeV neutron (GaAs) is 0.55 keV/cm^2 g [10].

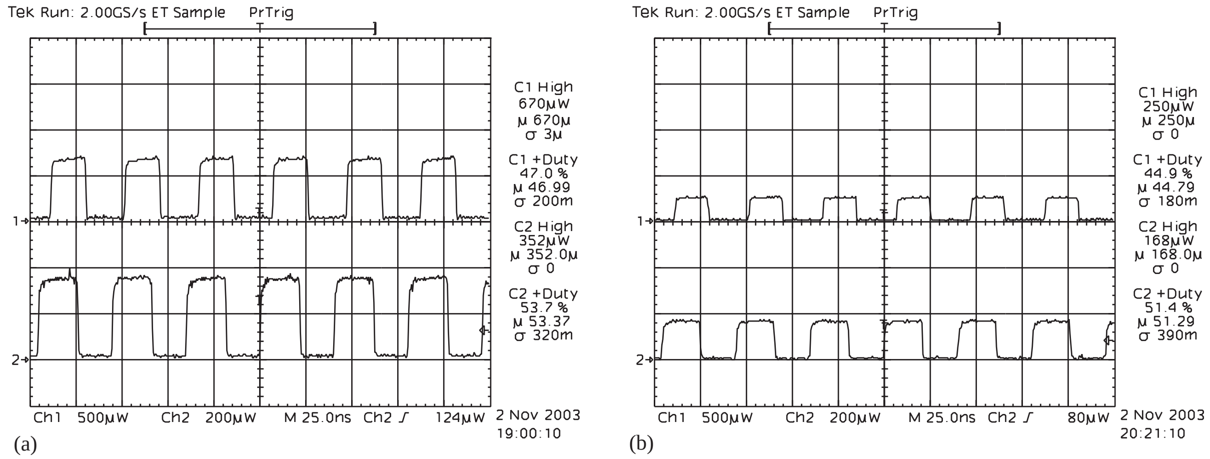

Fig. 4. Scope pictures of two laser light outputs measured by O/E probes (a) before and (b) after irradiation with 200 MeV protons for a total dose of 1.4 Mrad (GaAs) (30×10^{12} p/cm^2). The laser drivers were pulsed with ECL inputs at 50% duty cycle.

was shut off, the temperature measured on the laser substrate was quickly chilled back from 24.8 to 24.0 °C. The difference in temperature in each beam-on period caused a sharp fall in light output and was quickly recovered. After the irradiation, the light output measurement was extended for 24 h to monitor the annealing effect. The recovery in light power is about 10%.

The radiation-induced damage in the BiCMOS driver chip can be observed on the signal waveform. It was examined with the laser transmitters operated in AC mode in irradiation with 200 MeV protons at the Indiana University Cyclotron Facility (IUCF). The ECL inputs to the laser driver were sent by a pulse generator at 25 MHz, 50% duty cycle, with rise and fall times of less than 1 ns. The light outputs were measured with O/E probes and optical power meters. Shown in Fig. 4 are the scope pictures of two laser light outputs measured with the O/E probes for a total dose of 1.4 Mrad (GaAs) (30×10^{12} p/cm^2). Other than the amplitude, the signal waveform remains compatible after irradiation.

The light degradation was investigated for the dependence on beam intensity. Illustrated in Fig. 5a are the laser light outputs measured at IUCF with the beam flux rate increased from 3.4×10^9, 11.5×10^9 to 29.2×10^9/cm^2 s. The light power degradation rates versus the received dose are consistent. The duty cycle of the light signal observed by an O/E probe is also plotted. The width observed shows no indication of radiation damage. The duty cycle reduced slightly in a normal rate with lower laser light power.

With the laser transmitter operated in AC mode, the laser diodes were switched in cycles corresponding to half the irradiation period being powered on. The radiation damage was compared to the operation in DC mode at a constant laser current. In a test setup at the same beam intensity, the laser transmitter was operated at 25 MHz for the first period of irradiation, and then switched to DC mode at 100% duty cycle. The light signal amplitude of a laser channel measured by an O/E probe and those measured with optical power meters are plotted in Fig. 5b. The power meter measurements (integrating the light received) for AC mode signals at 50% duty cycle are scaled by a factor of two. The light degradation rates are consistent for the dose received, regardless of the laser diode operation at 50% duty cycle or at a steady current.

The light degradation measured with optical power meters were compared for the irradiations made with 30 and 200 MeV protons. With 30 MeV proton (Fig. 5c) the light outputs dropped by 35% for a total fluence of 10×10^{12} p/cm^2; with 200 MeV protons (Fig. 5b) it was 30% for 13.6×10^{12} p/cm^2.

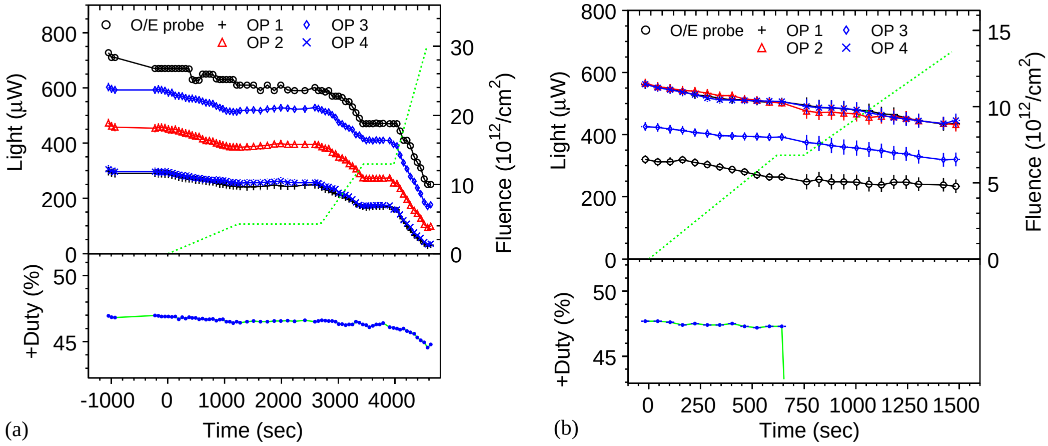

Fig. 5. Light outputs measured in irradiation with 200 MeV protons at IUCF. In (a) the laser channels were running in AC mode (ECL inputs at 50% duty cycle) in three flux rate; in (b) the laser was in AC mode and then switched to DC mode (+Duty = 0). The light power was measured by O/E probes and optical power meters (OP 1 to 4). The cumulative proton fluence is illustrated by the dashed line.

The NIEL factors are compatible for the two beam energies. The light degradation rates are consistent at about $3 \pm 2\%$ for a fluence of $1 \times 10^{12}\,p/cm^2$. The systematic uncertainty is large mainly due to the low statistics and sample deviation.

In summary, the radiation-induced damage for the laser transmitter was investigated with 30, 63 and 200 MeV protons. The light degradation observed is approximately linear to the radiation dose, for about 10% at a total dose of 200 krad, corresponding to an estimated integrated luminosity of more than $10\,fb^{-1}$ at CDF. The light degradation can be easily compensated by increasing the laser current or decreasing the operation temperature. The light signal waveform was examined with no indication of radiation damage. The radiation tolerance of the laser transmitter is expected to suffice for the CDF Run II operation.

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