VCSEL-based Custom Radiation Tolerant Optical Data Links

Ingrid-Maria Gregor[a], Mark Pearce[b*], John Dowell[c], Pedja Jovanovic[c], Andreas Kootz[a], Gilles Mahout[c], Igor Mandic[d], Tony Weidberg[d]

[a]Wuppertal University, D-42119 Wuppertal, Germany
[b]Royal Institute of Technology (KTH), S-10405 Stockholm, Sweden
[c]The University of Birmingham, Birmingham B15 2TT, Great Britain
[d]Oxford University, Oxford OX1 3RH, Great Britain

ABSTRACT

The Large Hadron Collider (LHC) will become operational in 2005 at The European Laboratory for Particle Physics (CERN). The LHC will be the highest energy proton-proton collider in the world. One of the electronic particle detectors which will operate at the LHC is called ATLAS. The environment for electronics placed within ATLAS is extremely hostile due to the high levels of radiation and the general lack of access to components during the expected 10 year lifetime of the experiment. It is planned to use custom radiation tolerant VCSEL-based optical links to transfer data from the ATLAS inner detector to remote data acquisition electronics. A low mass, non-magnetic and radiation tolerant VCSEL packaging has been developed for the most hostile region in the centre of ATLAS where the inner detector is located. The performance of the package is reported on. Qualification tests of commercial VCSELs are also described. The VCSELs were irradiated with neutrons (up to 8.10^{14} n(1MeV)/cm^2) and annealing studies carried out. Post-irradiation accelerated lifetime tests equivalent to a minimum of 3700 LHC operation years at a 0^{o}C operation temperature are reported on. The characteristics of VCSELs when operated in a strong magnetic field (up to 6 T) are also studied.

Keywords: Radiation tolerance, ageing, data link, custom packaging, magnetic field, particle physics.

1. INTRODUCTION

The Large Hadron Collider (LHC) will start operations at CERN, The European Centre for Particle Physics, in 2005 [1]. The LHC will collide counter-rotating beams of protons together, releasing an energy of $14\text{x}10^{12}$ eV at a rate of 40 MHz. The LHC accelerator has a circumference of 27km and straddles the Franco-Swiss border 100m underground. At LHC energies it is possible to recreate conditions that existed approximately 10ps after the creation of the universe and hitherto unobserved physical phenomena are expected to be observed. A prominent activity at the LHC will be to search for the Higgs Boson – a hypothesised particle, which if observed would provide a theoretical understanding of the origin of mass in the universe [2]. Large electronic particle detectors are located around the LHC accelerator to allow the particles produced from the proton-proton collisions to be tracked and characterised. One of these detectors is called ATLAS and is shown in figure 1 [3]. The ATLAS detector consists of many layers of electronic particle detector systems and is 45m long with a diameter of 25m. This paper describes a custom radiation tolerant VCSEL-based optical link developed to transfer data from the ATLAS inner detector [4] which is mounted around the evacuated pipe through which the proton beams travel through the centre of ATLAS.

2. THE ATLAS INNER DETECTOR AND THE OPTICAL LINK READ-OUT SYSTEM

The ATLAS inner detector consists of high resolution silicon strip detectors (SemiConductor Tracker, SCT) and a Pixel Detector mounted on a carbon fibre frame, as shown in figure 2. The structure has a diameter of approximately 1m and a length of approximately 7m. There are a total of $2.2.10^6$ individual silicon detector channels from 4088 silicon detector modules. The main task of the inner detector is to provide precision position measurements of charged particle trajectories as they traverse the detector. An accuracy of around 0.01mm for each ‘hit’ along the trajectory is sought. The detector system is highly granular to cope with the many charged particles produced on average from every LHC proton-proton collision. In order to facilitate momentum measurements of charged particles, the inner detector is immersed in a 2T magnetic field which runs axially along the proton beam direction. Hit data from the silicon detectors must be transferred to

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[*] Correspondence: Email: pearce@particle.kth.se; WWW:http://www.particle.kth.se/~pearce

a remote data acquisition system and control and clock information must be transferred to the silicon detectors. The large number of electronics channels makes the use of copper links unfeasible due to the large amount of dead material which would be introduced and problems from cross-talk and ground loops. It is therefore proposed to use custom VCSEL-based optical links to transfer data to and from the detector modules [5]. The optical link components mounted on the inner detector must be able to withstand the large levels of ionising radiation (500kGy for the pixel detector and 100kGy for the SCT)[1] and neutron radiation ($6.4.10^{15}$ n(1MeV)/cm^2 for the pixel detector and $1.3.10^{15}$ n(1MeV)/cm^2 for the SCT) expected over the 10 year lifetime of ATLAS.

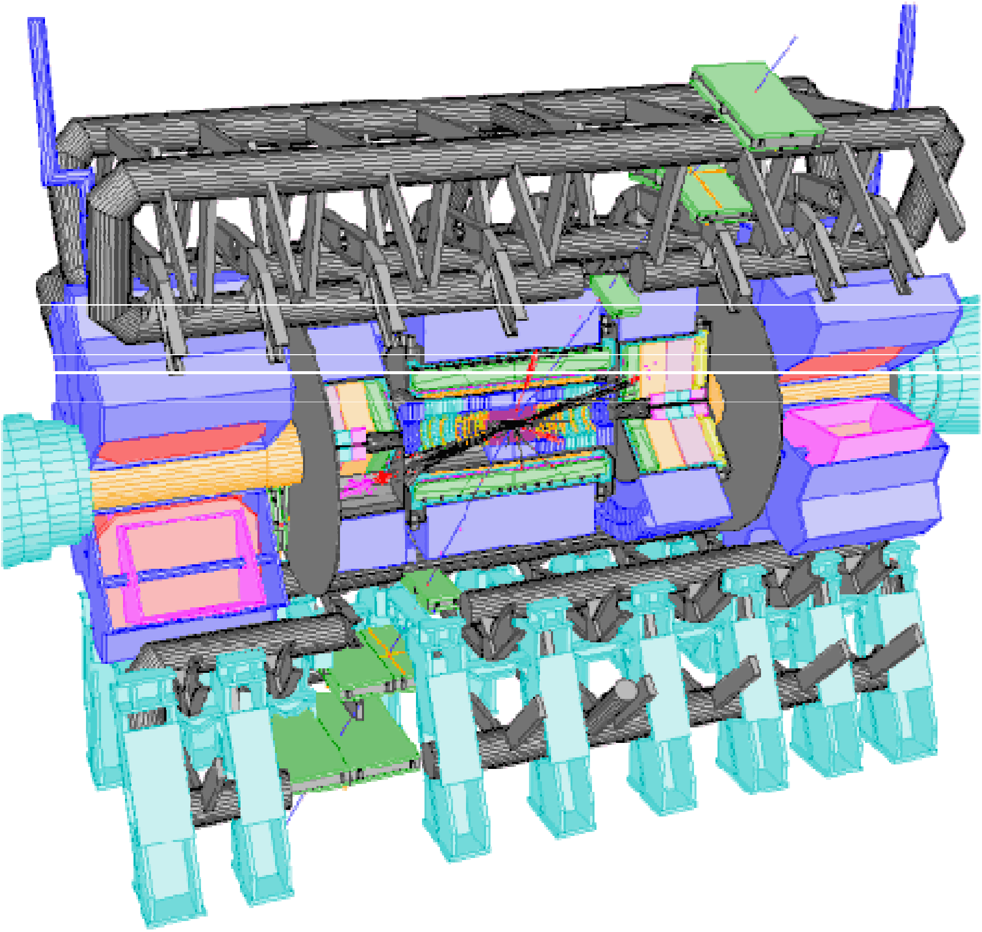

Figure 1: The ATLAS experiment. Proton beams enter from the left and right and collide in the centre of the experiment. The experiment consists of many layers of electronic particle detectors and is 45m long and has a diameter of 25m. The inner detector is the first detection layer located closest to the proton-proton interaction point. VCSEL-based optical links are used to transfer data from this detector to remote data acquisition systems.

Neutron radiation is potentially more damaging to VCSEL emitters as radiation induced damage can introduce non-radiative levels into the band-gap of the GaAs junction [6]. It is important that the link components mounted on the inner detector are non-magnetic to avoid perturbing the inner detector magnetic field. The components must also have a low mass so as small a cross-section as possible is presented to particles produced from the primary proton-proton interaction. Additional interactions in non-instrumented regions of the detector would compromise the quality of momentum measurements.

The overall architecture of the optical link system is shown in figure 3. Each opto-package consists of two data links running from the detector to a remote data acquisition system and one 'TTC' link which carries trigger, timing and control signals. Each link runs over a distance of up to 100m. The data links operate at a rate of 40Mb/s using a Non Return to Zero

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[1] The pixel detector is mounted closer to the proton-proton interaction point than the SCT. The doses and fluences quoted are worst case levels for the parts of the detector system closest to the proton-proton interaction point.

(NRZ) format. The TTC link uses Bi-Phase Mark (BPM) encoding to transfer the LHC 40MHz master clock (the proton-proton collision frequency) along with 40Mb/s control data. The laser driver and TTC receiver chips are realised in the AMS 0.8µm BiCMOS process [7]. Although not a qualified radiation hard process, special design rules are followed and only npn bipolar transistors are used to ensure sufficient radiation hardness [8].

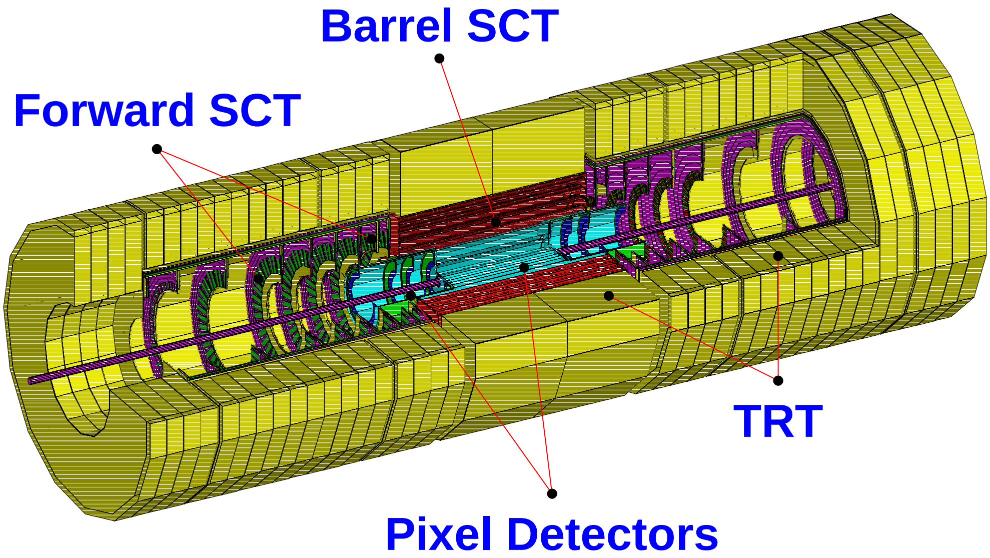

Figure 2: The ATLAS inner detector. Optical link developments to transfer data from the pixel and SemiConductor Tracker (SCT) detector systems are described in this paper. The Transition Radiation Tracker (TRT) detector has a copper read-out system and is not addressed in this paper.

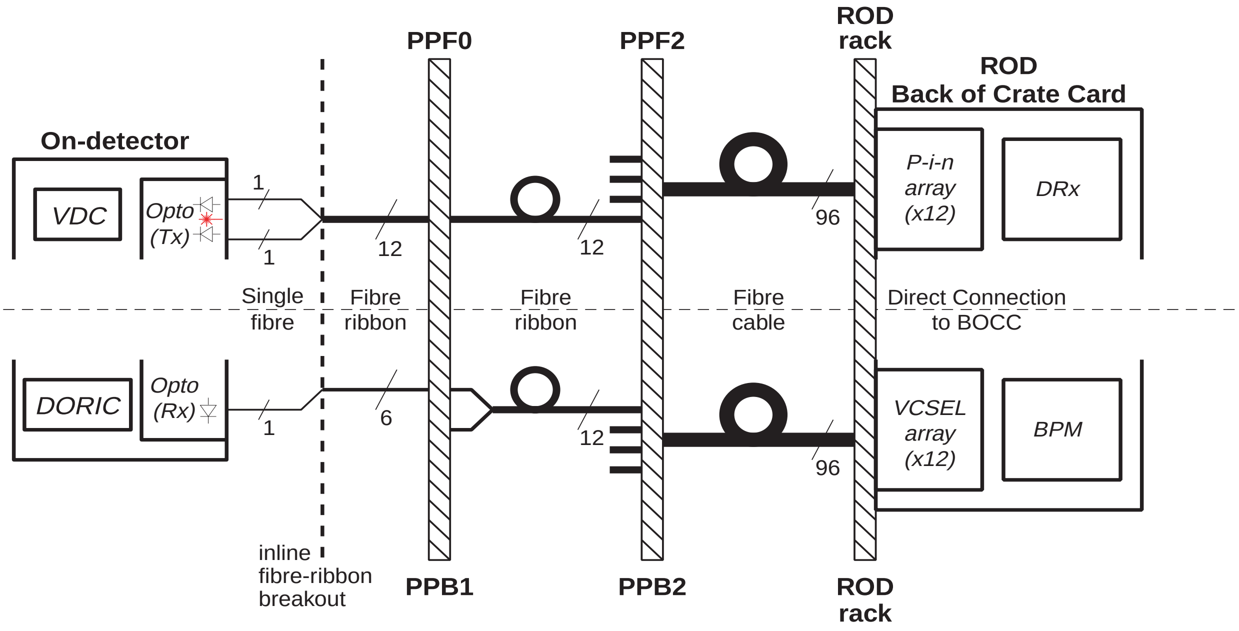

Figure 3: The inner detector read-out link architecture. The 'VDC' is a the VCSEL driver chip, 'DORIC' recovers the clock and control data, 'DRx' decodes the hit data sent from the silicon detectors and 'BPM' performs the Bi-Phase Mark encoding of the Trigger Timing and Control (TTC) data sent to the silicon detectors. Patch panels are denoted 'PPB(F)n'.

Due to the constraints listed above, the optoelectronic components mounted on the inner detector must be packaged in a custom housing. There are approximately 7000 opto-packages in total. Each package contains two VCSEL emitters operating at 850nm and an epitaxial silicon PIN-diode, as shown in figure 4.

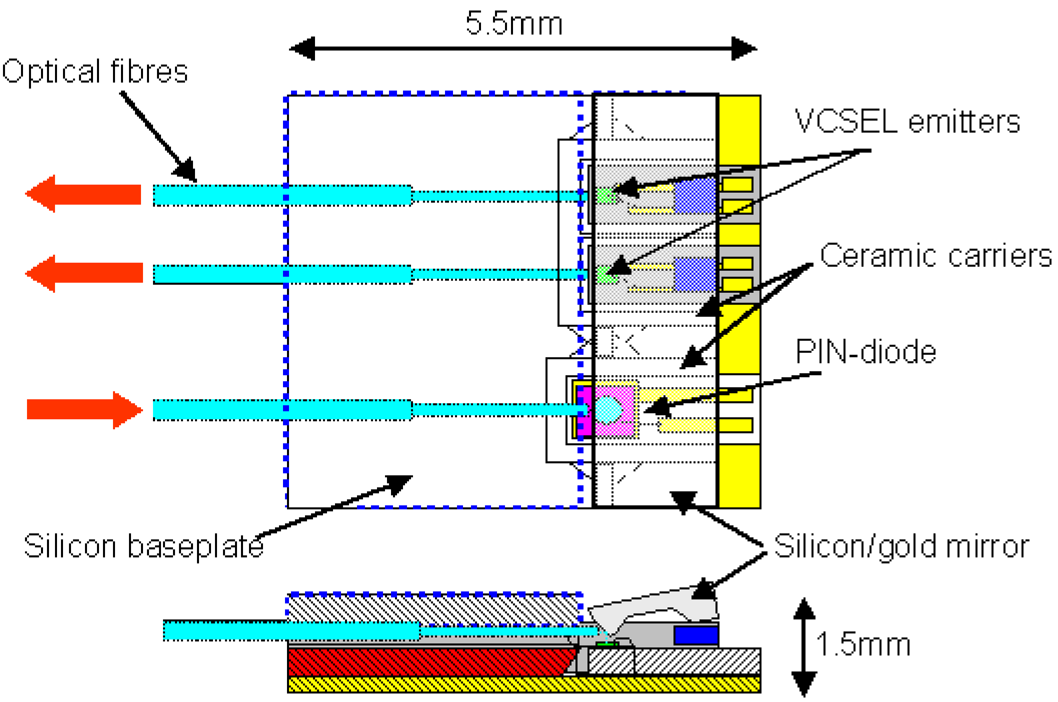

Figure 4: The custom opto-package. Two VCSEL emitters and a PIN-diode are housed in a low mass, radiation tolerant silicon / ceramic package. Fibres attached to the package lid are pigtailed directly to the components with the aid of a gold-coated silicon mirror.

The extreme lack of space prevents the use of industry standard connectors and fibres are pig-tailed directly to the optoelectronic components. A 50/125 step index fibre manufactured by Fujikura is used. This fibre has a pure silica core of diameter 50µm which is surrounded by a 5µm thick fluorine doping. This depresses the refractive index and gives the fibre a step index profile. A pure silica cladding extends up to a diameter of 125µm. Due to the lack of dopants in the core, the fibre is extremely resistant to radiation [9]. The VCSELs and PINs are mounted on ceramic carriers which form part of a silicon package. The overall package is approximately square with sides of 5.5mm and is 1.5mm high. The packages were developed in collaboration with Marconi, UK. The fibres are located in v-grooves etched into a silicon lid assembly. Light is bent through 90 degrees into the optoelectronics by a silicon mirror. To enhance reflectivity whilst avoiding passivation problems, the mirror surface is sputtered with gold. No coupling lenses are required. The fibres can be aligned to the base of the package using reference features etched into the lid and base. The alignment procedure is entirely passive which greatly reduces production costs. The opto-package presents 0.014 radiation lengths[2] to incoming particles.

The opto-packages are mounted onto a flexible 'copper-on-kapton' cable assembly shaped like a dog-leg, as shown in figure 5. The dog-leg is secured to the carbon fibre support structure of the inner detector and carries power, data and control signals to the silicon detectors. The optoelectronics is secured to a thin aluminium plate mounted on the dog-leg and provides support as well as thermal connection to the inner detector cooling system. At present, the complete optoelectronic

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[2] The radiation length of a material is the distance over which the energy of an incident electron beam is reduced by a factor 1/e due to bremsstrahlung processes.

system consists of a thick film circuit printed onto a ceramic substrate which carries the VCSEL/PIN package and the laser driver and receiver chips. For the final version it is planned to use ‘flex-rigid’ technology, where kapton interconnects are incorporated into a multi-layer circuit board assembly. During production, dog-legs will be formed into harnesses which can be fastened to the inner detector structure with connections made to the silicon detectors. During harness construction, the delicate optical fibres are attached last of all and routed to a compact patch panel mounted on the harness. Data and control fibres will be grouped into separate 12-way ribbons to allow MT connectors to be used at the patch panel. This approach also allows the use of VCSEL and PIN-arrays off-detector which allows a high channel density to be realised in a standard VME crate environment.

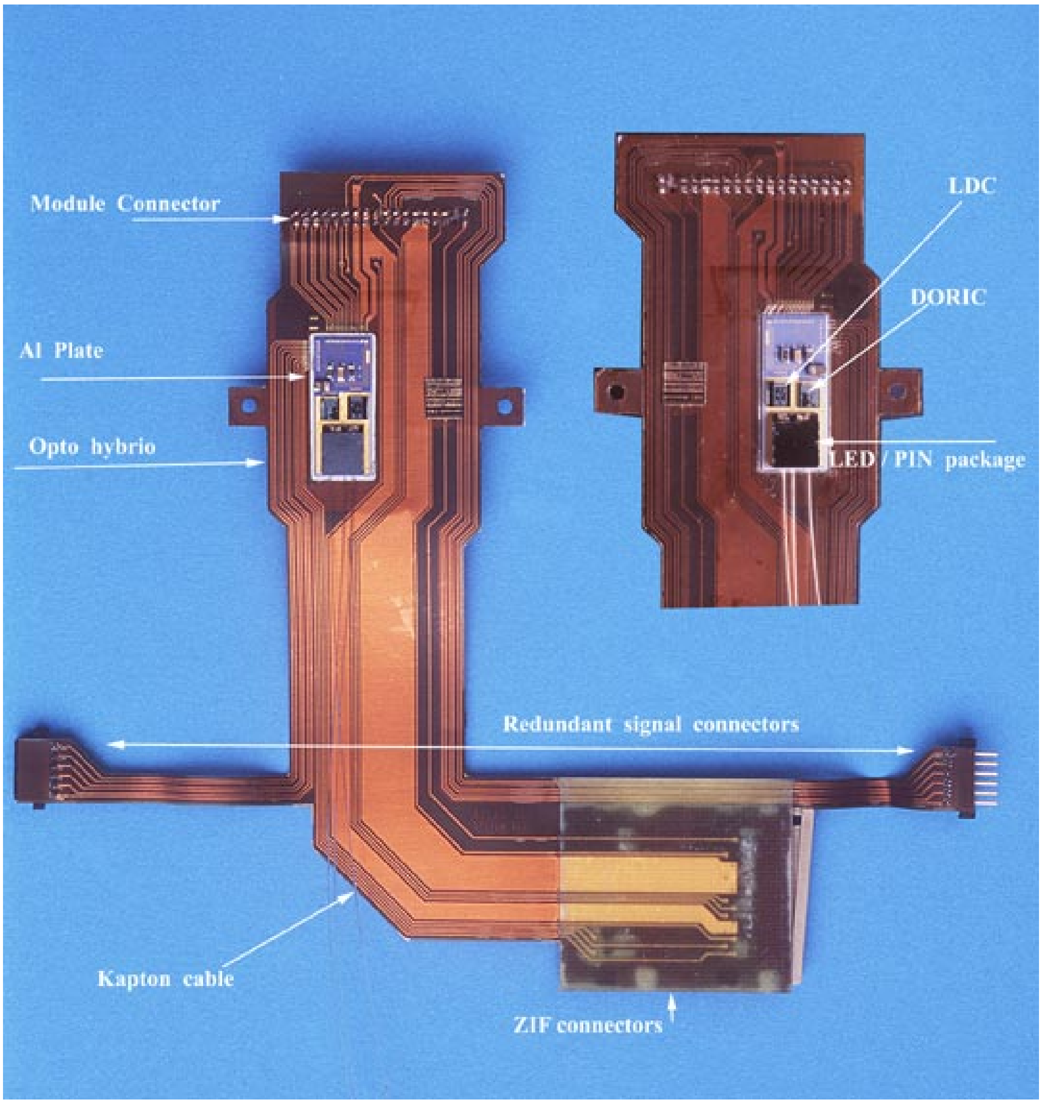

Figure 5: The ‘copper-on-kapton’ dog-leg support structure for the opto-packages. This photograph shows an earlier design when LED emitters were being evaluated.

3. RESULTS

In this section results from the development of the inner detector optical link packages are presented. The stress is laid on the performance of the custom packaging technique and the performance of VCSEL emitters in an ATLAS-like environment. The performance of VCSEL emitters when exposed to high levels of neutron radiation is therefore investigated. All the VCSELs used in the tests reported here were supplied by Mitel Semiconductor [10]. Results on the radiation tolerance of epitaxial silicon PIN-diodes are presented elsewhere [11].

4.1. DC system tests

Figure 6 shows the output power -vs- bias current characteristics of two VCSELs in an opto-package, measured with an optical oscilloscope probe. The behavior of the two VCSELs is consistent and even for a modest bias current of 10mA, around 0.5mW of fibre coupled power is recorded.

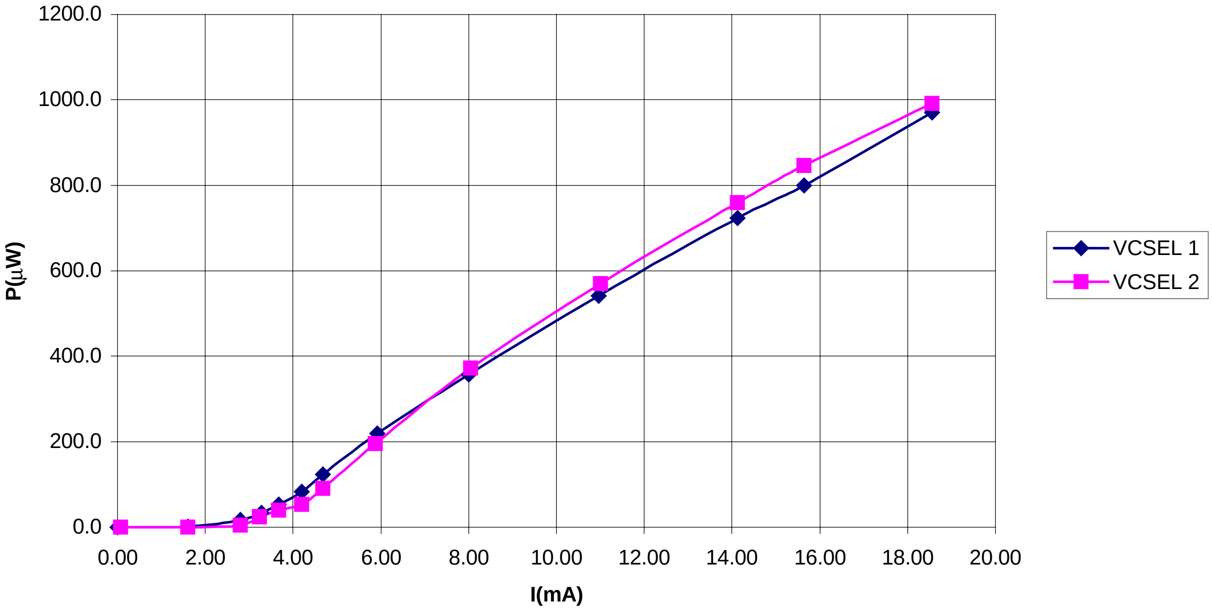

Figure 6: Fibre-coupled output power of the packaged VCSELs.

4.2. AC system tests

The output from the VCSELs mounted in an opto-package was measured with an optical oscilloscope probe. The VCSELs were driven with a 10mA drive current modulated at 20MHz – corresponding to 40Mb/s of NRZ data. The waveform is very clean and exhibits rise and fall times around 1ns. To check the noise and stability of the VCSEL-fibre system a cumulative image of the output waveform was inspected. The result shown in figure 7 shows that the system is stable and that there is no significant laser noise due to spurious reflections induced by a poor fibre coupling.

4.3. Neutron irradiations and annealing studies

A group of 20 VCSELs packaged in standard 'ST' receptacles was spit into groups of five and irradiated using a spallation neutron source at the Rutherford Appleton Laboratory (RAL), UK. Due to the short irradiation time and inaccessibility of the components during irradiation, no on-line measurements of the induced output power attenuation were possible and the VCSELs were not biased. In figure 8 the relative light output (RLO)[3] is plotted as a function of time after the end of the irradiation period while a bias current is applied. The bias currents and irradiation levels are denoted on the figure. Each curve shows the average behavior for a group of VCSELs. For a given irradiation level, a larger bias currents results in a

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[3] Defined: RLO = (light output power before irradiation) / (light output power after irradiation).

faster annealing process as expected. For the highest neutron fluence of 8.10^{14} n(1MeV)/cm^2, 80% of the pre-irradiation light output power can be recovered in approximately 2 hours with a bias current of 20mA.

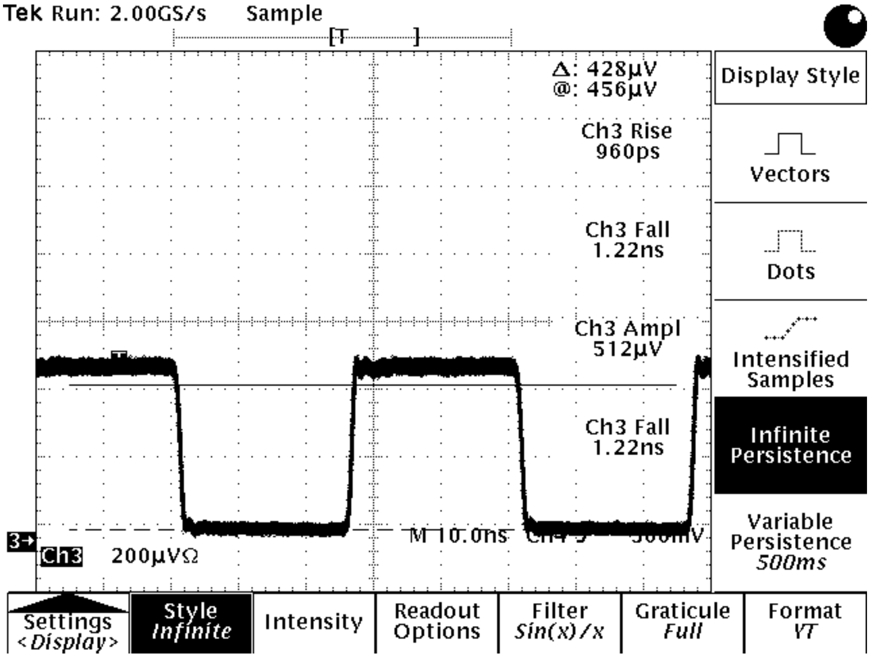

Figure 7: A cumulative image of the output waveform from the opto-package when operated at 40MHz.

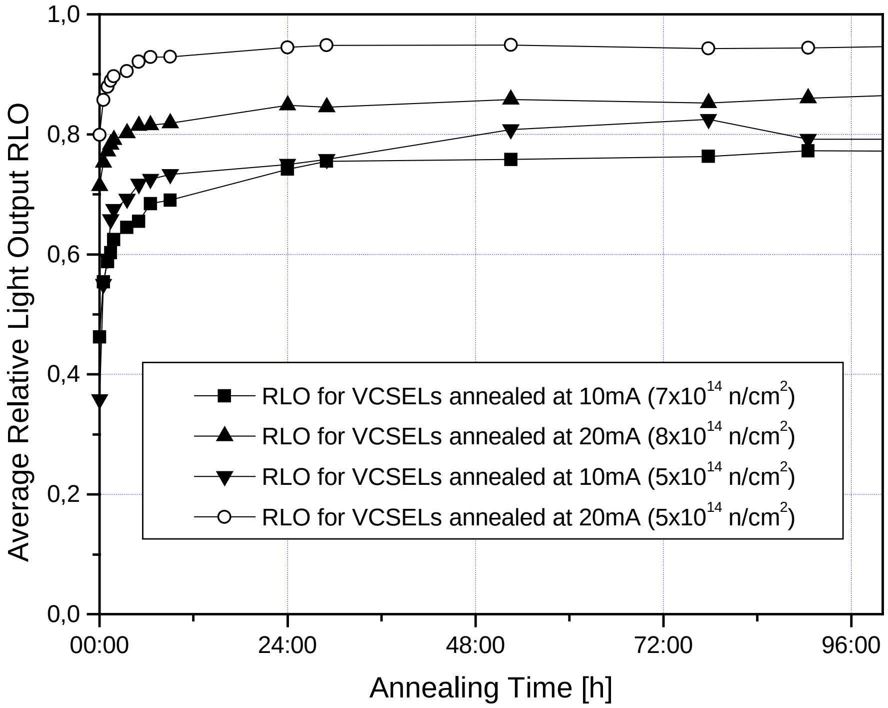

Figure 8: The annealing characteristics of VCSELs after irradiation with neutrons.

4.4. Ageing studies

Once a fluence of 4.10^{14}n/cm^2 had been reached during the irradiation period, the VCSELs were divided into two equally populated groups and were biased at 20mA or 25mA. All VCSELs were held at a temperature of 40^{o}C for a period of 38 days. The Arrhenius Equation can be used to calculate the acceleration factor (AF) for the VCSEL ageing compared to normal operating conditions. The Arrhenius Equation is defined as:

$$AF = \frac{TTF_1}{TTF_2} = \left(\frac{I_{F1}}{I_{F2}}\right)^2 \exp\left[\frac{E_a}{k_B}\left(\frac{1}{T_{J2}} - \frac{1}{T_{J1}}\right)\right]$$

where: TTF denotes time to failure, I_F denotes the bias current (20mA or 25mA during tests and 10mA during ATLAS operation), E_a is the VCSEL activation energy (1.0eV [12]), k_B is Boltzmann's constant and T_J is the VCSEL junction temperature (40^{o}C during tests and 0^{o}C during ATLAS operation). An additional acceleration factor of 12 is also applied to account for the LHC only operating for a third of the year, the average link occupancy being 50% and an equal population of 0's and 1's sent down the link. Using this formalism, an operational period of 3700 (5900) LHC-years has been simulated for the VCSELs biased at 20mA (at 25mA). No failures (defined as a –3dB drop in the VCSEL output power) were observed during the ageing test. From these results it is possible to predict that a maximum of 0.2% (90% confidence level) of the VCSELs will fail during the 10 year lifetime of the ATLAS experiment. These results are compatible with the findings of standard ageing tests with non-irradiated VCSELs, as reported by Honeywell and Mitel during recent workshops dedicated to the use of optical link technologies in particle physics experiments [13]. Earlier studies of VCSEL ageing within the ATLAS inner detector community used non-commercial VCSELs supplied by Sandia National Laboratories [6].

4.5. Operation in a strong magnetic field

As dictated by the operating environment, it is important to check that the link performance is not compromised by the presence of a 2T magnetic field. To evaluate this an opto-package containing a VCSEL and laser driver was mounted on a hinged platform inside the bore of a superconducting magnet which could be ramped between 0T and 8T. In practice, ramping had to be stopped at 6T to prevent the fringe field interfering with measurement equipment. The output power –vs-bias current characteristics of a VCSEL at different field strengths and platform angles (90^o (0^o) indicates that the packages are perpendicular to (parallel to) the magnetic field) is shown in figure 9. No significant effect due to the magnetic field is observed. A similar null result was obtained when investigating the rise and fall time of a 40MHz signal sent to the VCSEL.

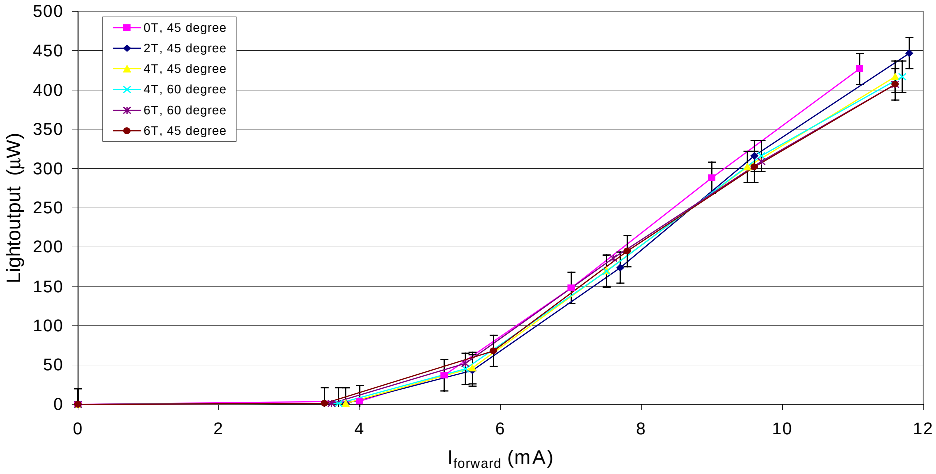

Figure 9: The output characteristics of VCSELs when operated in a magnetic field.

4. CONCLUSIONS

The ATLAS experiment is one of the next generation of particle physics experiments, due to start in 2005, which will give physicists an excellent opportunity to study conditions prevalent 10ps after the creation of the universe. The ATLAS experiment is a large and highly segmented electronic particle detector. Data from the huge number of electronics channels will be transferred away from the ATLAS inner detector by VCSEL-based optical links. Custom packaging developments for the 40Mb/s optical link are described. A low mass, radiation tolerant and non-magnetic packaging has been designed. Initial tests show that both the DC and AC optical properties of the package are stable and satisfactory. The neutron radiation tolerance of VCSELs from Mitel Semiconductor has been characterised. The radiation induced attenuation of the light output power can be partially annealed out by biasing the VCSELs after irradiation. Approximately 50% of the attenuation can be annealed out immediately. Up to 90% of the pre-irradiation light output levels have been recovered over a time period of days. The results suggest that if in practice VCSELs are operated with a bias current of 10mA there should be brief 20mA bias current annealing sessions implemented when necessary to remove radiation induced attenuation. After irradiation, accelerated ageing studies were carried out. From the results, a maximum of 0.2% (90% confidence level) of the VCSELs in the inner detector link are expected to fail (-3dB loss in output power) after 10 years of ATLAS operations. The neutron fluences reached during tests to date do not reach the maximum fluences expected during ATLAS running. Approximately 13% (62%) of the maximum pixel (SCT) fluence is reached. More tests are planned to complete this study for the worse affected parts of the detector. Finally, it has been shown that the DC and dynamic characteristics of VCSELs are insensitive to magnetic fields up to the test ceiling of 6T. In summary, VCSELs are a robust light source and withstand well the operating demands of the next generation of particle physics experiments.

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