Optical links for the CMS Tracker

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Abstract

The development phase of the optical data transfer system for the CMS tracker is nearing completion. This paper focuses on three types of validation tests carried out by CERN on Commercial-Off-The-Shelf electro-optic devices: functionality tests, environmental tests and reliability tests. The project status and the preparation for production are also reviewed.

1. INTRODUCTION

The architecture of the CMS tracker analogue readout system is shown in Fig. 1. The ~50000 uni-directional links are based on edge-emitting laser transmitters and pin photodiode receivers operating at a wavelength of 1310nm. In every single-mode fibre, 256 electrical channels are time-multiplexed at a rate of 40MSamples/s. Two in-line patch-panels fan-in the fibres originating from the transmitters, first to a 12-way ribbon, and then to an 8-ribbon cable carrying 96 fibres away from the detector to the counting room. All system components situated inside the detector volume (drivers, lasers, fibres and connectors) must be non-magnetic, radiation resistant and reliable.

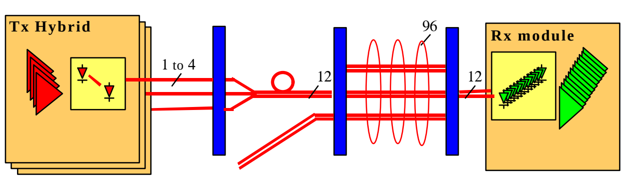

Fig. 1. Block diagram of the analogue readout link

Table 1: Analogue optical link requirements

Characteristic	*Typical requirement*
Analogue coding scheme	Pulse Amplitude Modulation 40MSample/s
Peak SNR	48dB (250:1)
Integral linearity deviation	2 %
Bandwidth	100MHz
Settling time to 1%	18ns

The analogue link requirements are summarised in Table 1. They are modest in comparison to what is typically achieved in other analogue distribution networks such as cable TV, but must be met at a very low cost, in a harsh environment, and for a large quantity of channels.

The ~2000 bi-directional digital links (Fig. 2) used for control and timing distribution are based on almost identical components as the analogue readout system, since the small number of digital channels does not justify the effort of selecting and qualifying specific devices

The only differences between analogue and digital systems are the number of fibres per ribbon (8 compared to 12) and the fact that the receiver modules placed inside the detector need to be built with radiation resistant photodiodes and discriminating amplifiers.

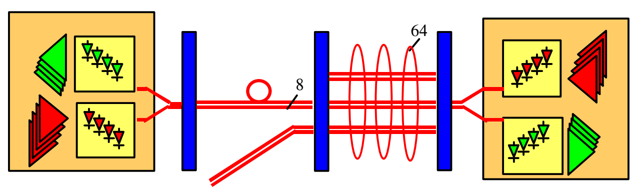

Fig. 2. Block diagram of the digital control link

Table 2: Digital optical link requirements

Characteristic	*Typical requirement*
Bit Rate	40Mb/s
Bit Error Rate	10^{-12}
Sensitivity	-30dBm
Bandwidth	100MHz
Jitter	<0.5ns

The digital link requirements are summarised in Table 2. The operation frequency will be 40Mb/s for the data and 40MHz for the clock channels.

The development options, choices and component types selected to be used in the tracker optical data transfer system have been described elsewhere [1]. Also, results obtained with 4-channel prototype parallel analogue links have been reviewed in [2]. This paper presents the validation tests performed on commercial components before specifications are frozen and the production phase can be started.

2. COMPONENTS VALIDATION PROGRAM

Apart from the custom designed electronics for the laser-drivers [3] and photodiode-receivers [4], all optical link components to be used in the CMS tracker are based on Commercial-Off-The-Shelf products (COTS). Slight deviations from the standard manufacturing process are only allowed to meet specific functionality requirements such as low back-reflection (for analogue performance), or particular environmental constraints such as high magnetic field. For instance, whereas distributed feed-back (DFB) edge emitting lasers are known for their superior analogue performance, and even though pure silica core fibre is usually recommended for radiation sensitive applications, standard low-cost Fabry-Perot lasers and telecom-grade single mode fibre is specified for the CMS-tracker optical links. This development strategy has the advantage of minimising development and system cost, but dictates the launch of extensive validation programmes to confirm that as wide a range of COTS as possible can be used reliably in the CMS tracker environment.

The optical link COTS devices consist of semiconductor lasers and photodiodes, as well as optical fibre and connectors. They are targeted at the telecom market and are of the single-mode, long wavelength type. Such telecom components are usually qualified for digital data transmission and for operation in standard (but nevertheless stringent) environmental conditions. Their use in an analogue system and in an environment like LHC must thus be carefully checked.

The components validation programme, devised to minimise the risk of using COTS in the CMS-tracker application, has three parts:

a) The in-system functionality tests must demonstrate that the telecom-grade components being evaluated meet the system-level requirements. For instance, standard Fabry-Perot lasers must be shown to satisfy the low noise requirements of an analogue readout system.

b) The environmental tests must subject the devices under evaluation to stress conditions not part of the standard telecom qualification programmes. For instance, telecom-grade single-mode fibre must be shown to be radiation-resistant, and components packages must be proven to be non-magnetic.

c) The reliability tests finally must ensure that environmentally stressed components (in particular irradiated devices) will have sufficient reliability to operate within specs during the lifetime of the experiment.

The validation programme described below in more detail is thus not simply a clone of standard telecom qualification procedures. It is an additional test, specifically matched to the operational and environmental requirements of the experiment. In this paper, we illustrate, as an example, the description of the validation-programme with results obtained with Fabry-Perot edge emitting lasers supplied by ITALTEL (Milano). Similar validation tests are being performed on all components considered to be used in the CMS-tracker optical links.

2.1. In-system functionality tests

The in-system functionality tests evaluate the system performance with the device under test embedded in a reference analogue optical link. It is assumed that devices meeting the analogue link requirements will also be good candidates for the digital links. The investigated system parameters are dynamic range, linearity and pulse response. The measurement procedure is described in [5]. The results are compared with the system-level specifications and presented in a way that allows comparison between devices and manufacturers.

Figure 3 shows, for example, the optical link static transfer characteristic measured with 20 laser transmitters of the same type. The spread in gain is due to variations in laser output coupling efficiency and connector insertion loss. The output noise in the full system bandwidth is also plotted in Fig. 3, normalised by the full scale signal amplitude, as a function of link input voltage.

This set of plots is reduced to 1 point per device in Fig. 4, where deviation from linearity and noise are computed, and normalised to a chosen fraction of the full scale signal. Integral deviation from linearity and peak signal to noise ratio can thus be quickly evaluated for any device operating in a given range. For instance, assuming an input voltage full scale of 800mV, one can quickly asses that in the first quarter of the operating range (i.e. 200mV input), a peak signal to noise ratio better than 140:1 and a linearity deviation of less than 0.6% are typically obtained with the tested devices. In the full operating range (i.e. 800mV), the peak signal to noise ratio of the same devices is greater than 300:1 for a linearity deviation of less than 1%.

The pulse response of the system is dictated by the custom designed transmitting and receiving electronics. It shows little dependence on the COTS under test. Typical rise time values are of the order of 3ns.

The in-system test results for laser transmitters shown above indicate that the investigated devices meet the

CMS-Tracker analogue link requirements, despite the fact they were developed as digital transmitters for telecom applications.

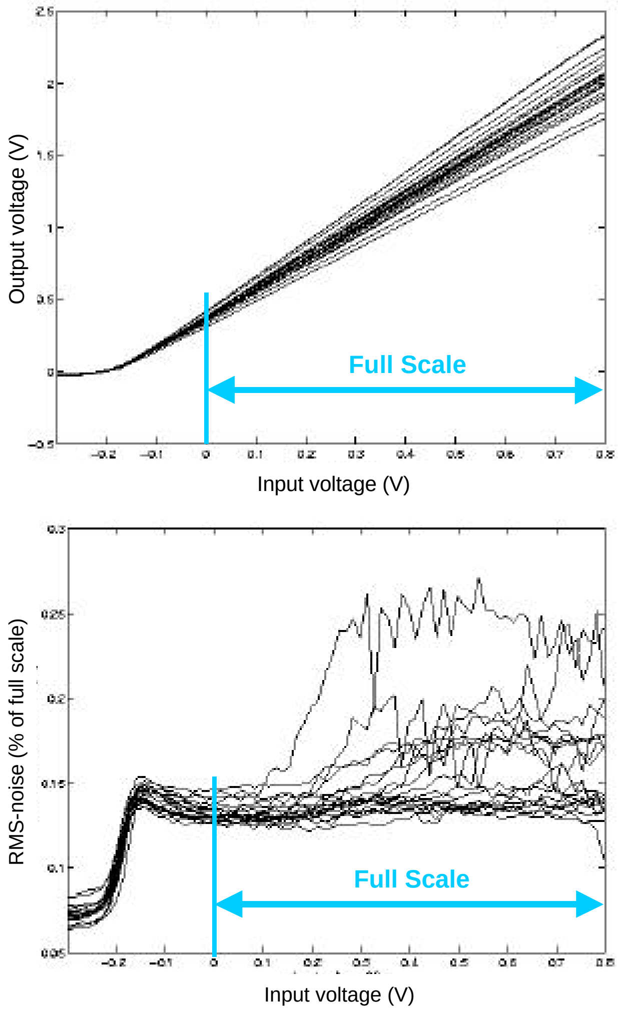

Fig. 3: Output (top) and Noise (bottom) performance of the reference optical link versus input voltage, for the 20 laser transmitters under test.

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Fig. 4: Peak signal to rms noise ratio versus integral non-linearity in a 200mV input range (one quarter of link full scale) for the 20 lasers characterised in Fig. 3. For each device, the mean value and standard deviation in the considered range are shown.

2.2. Environmental tests

In the environmental evaluation procedure, the front-end components are tested for resistance to magnetic field and radiation. It is assumed that other usual qualification tests such as temperature cycling, vibration, etc. will have been performed by the manufacturers as part of the standard telecom qualification programmes.

The magnetic field resistance test is a simple mechanical test whereby the force exerted by the field on the device under evaluation is estimated.

The irradiation tests monitor in-situ the changes in the device performance resulting from radiation damage and subsequent annealing. They are carried out at room temperature with the devices operated under typical bias conditions. Both neutron and gamma irradiations are performed.

Figure 5 compares the threshold currents of 30 irradiated lasers to pre-irradiation values. The devices were irradiated with neutrons at room temperature to a total fluence of the same order of magnitude (2.5 to 6 $\times 10^{14}$ n/cm^2) as the maximum expected hadron fluence (pions, neutrons, protons etc. combined) in the CMS tracker over 10 years of operation. The irradiated samples were stored, electrically shorted, at room temperature for up to 15 months. Based on our earlier studies[6], we estimate that 30% of the initial radiation damage in the lasers annealed during this period.

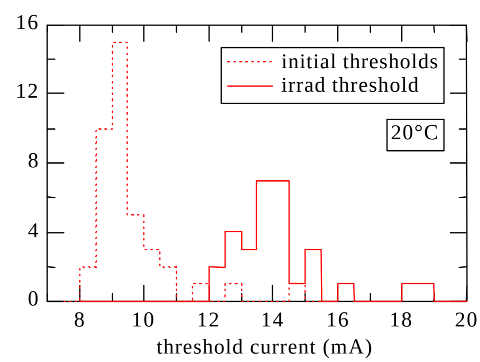

Fig. 5: Threshold currents for the irradiated lasers. Data shown are the pre-irradiation values (30 plus 10 reference samples) and those measured after irradiation and annealing (30 samples).

A thorough discussion of the radiation damage effects for this particular type of laser can be found elsewhere for tests carried out using neutrons and other radiation sources [7]. Test results have also been published for optical fibre [8], connectors [9] and pin photodiodes [10]. Comparative validation results obtained in the framework of the market surveys for lasers and connectors will be available soon.

2.3. *Reliability tests*

Manufacturer-qualified, telecom-grade COTS are known to be highly reliable. However, it is not known if radiation damage will influence this reliability. Component reliability is often categorised into three domains: early, mid-life, and old-age failure, each with several different mechanisms [11] that contribute to the failure rate.

Early failures (sometimes termed 'infant mortality') are usually intrinsic to the device and are eliminated by a burn-in, or purge-test, inducing weak devices to fail before the components are employed in the field.

The mid-life failures can be subdivided into two parts, the first being simply due to the tails of the early and long-term failure distributions. The remaining failures are collectively grouped together as 'sudden' or 'random' failures, which are catastrophic failures often triggered by external factors such as electrical or mechanical shocks, depending upon the operating environment.

Long-term failures are usually dominated by 'wearout'. For the optical link components inside the CMS tracker the most important wearout failure modes are likely to be resulting from a combination of radiation damage and intrinsic wearout degradation.

Ageing tests of irradiated components have been performed on semiconductor lasers and photodiodes, as well as optical connectors. As example, we show in Fig. 6 ageing test results obtained with 30 neutron-irradiated (see 2.2) and 10 unirradiated lasers. The laser threshold current versus time is plotted for all the devices tested. At 80°C (20°C) the unirradiated devices have initial threshold currents of 21-31mA (8-11mA) and the irradiated devices have values of 28-55mA (12-19mA), this larger variation being mainly due to the different neutron fluences received by the various devices. Overall, the rates of wearout degradation of the laser threshold currents are very small, <0.4mA/1000hours in the unirradiated devices. For the irradiated devices, annealing of the radiation damage is the main effect. Only a few of the irradiated devices show increases in threshold current. The device labelled A, which has the most degradation, should have actually been rejected by the supplier following burn-in, based on its high threshold current increase during the purge phase.

The irradiated lasers continued to anneal throughout the 4000 hours at 80°C, therefore the ageing related wearout was obscured for these devices and a wearout rate could not be accurately determined. However, as the annealing rate decreases with increasing time[6], the results suggest that the wearout rate of the irradiated lasers is not significantly greater than in the unirradiated samples.

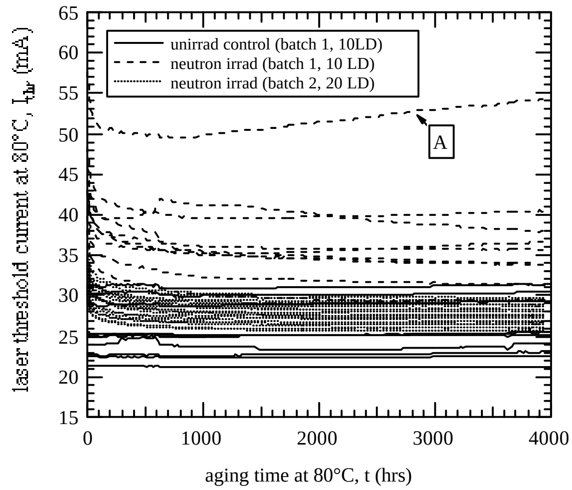

Fig. 6: Laser threshold current during ageing.

Failure rates can be extrapolated from ageing test results such as shown in Fig. 6, by defining failure criteria and calculating acceleration factors. A detailed estimation of the reliability of irradiated lasers and pin-diodes in the CMS tracker is in progress. Reliability tests have also been performed on optical connectors: repeated mate/demate tests on irradiated MT ferrules are reviewed in [9].

3. PROJECT STATUS

The feasibility of an analogue optical link meeting the CMS-Tracker requirements (both in terms of functionality and environmental resistance) has been demonstrated [2]. The elements not yet in their final form are: the laser driver ASIC, which is still implemented in a radiation soft technology, the 12-channel analogue receiver ASIC, which is currently under test, and the receiver module (combining photodiodes and amplifiers in one housing), which is being developed in industry. Options are still open for the optical connectors of the first patch panel, inside the CMS detector. They will remain so until the exact layout and modularity of the tracker is frozen.

Digital links operating at 40Mb/s and based on driver, laser, connector and fibre components identical to the analogue-link ones have been successfully tested in the laboratory. A full custom rad-hard digital receiver chip has been designed [4]. A radiation resistant InGaAs pin diode in a low-mass non-magnetic package has been identified, tested and validated.

An effort is now being made to integrate the optical links into complete readout and control systems. For instance, prototype 4-channel analogue links have been distributed to various institutes involved in the construction of the CMS tracker. A complete system evaluation in a 25ns test-beam at CERN is scheduled for May 2000.

In an attempt to reduce the uncertainties of optical link cost, a tendering procedure has been started for the bestdefined components in the system. Market surveys have been issued for semiconductor lasers and single-mode optical connectors. Samples from various manufacturers are currently being evaluated, following a validation programme consisting of interleaved functionality and environmental tests similar to the ones described in sections 2.1 and 2.2. Market surveys for optical fibre, ribbon and cable, as well as detector modules will follow in 2000. It is planed to issue the first calls for tender in the first half of 2000.

4. CONCLUSION

The combined needs for radiation resistance, high reliability and analogue functionality at low cost present a unique challenge. The use of COTS lasers, fibres, connectors and photodiodes benefits from the rapid progress made by telecom components suppliers and allows to reach cost levels compatible with the experiment budget. It however dictates the need for a thorough validation programme.

Three types of validation tests are being carried out on COTS electro-optic devices supplied by industry: a) functionality tests (compliance to system specifications), b) environmental tests (resistance to radiation and magnetic field) and c) reliability tests (ageing of irradiated components).

a) Functionality tests have confirmed that a variety of commercially available lasers, fibres, connectors and pin diodes can fulfil the CMS-tracker application requirements. Due to the stringent installation schedule, emphasis has first been placed on the evaluation of laser transmitters. A validation scheme has been worked out to compare different devices proposed by various manufacturers. Similar programmes are being prepared to evaluate optical connectors and cables.

b) Irradiation tests have been carried out extensively on lasers, pin-diodes, fibres and connectors with various sources and at different energies. In order to better understand the real long-term performance of irradiated components in the CMS-tracker environment, the annealing behaviour of laser damage versus operating temperature and bias current is also being investigated. A model extrapolating laser parameter drift as a function of detector operation time and position is under development.

c) Reliability tests of irradiated lasers and pin-photodiodes have been performed with devices operated for over 4000 hours at 80°C. Also, irradiated connectors have been subjected to repeated mate/demate cycles. Results suggest that only a minor fraction of the optical links is likely to fail during the lifetime of the experiment. Qualification tests on significant quantities of devices will take place during the pre-production phase of the project.

To have a better understanding of the volume costs of both analogue and digital optical links, the tendering process has been started for laser transmitters and connectors. Cost information will be available in the middle of 2000.

5. REFERENCES

[1] G. Hall, G. Stefanini, F. Vasey, "Fibre optic link technology for the CMS tracker", Technical note CMS Note 1996/012, Dec. 1996.

[2] F. Vasey, C. Aguilar, V. Arbet-Engels, C. Azevedo, G. Cervelli, K. Gill, R. Grabit, F. Jensen, C. Mommaert, P. Moreira, "A 4-channel parallel analogue optical link for the CMS-Tracker", proceedings of the fourth workshop on electronics for LHC experiments, Rome, September 21-25, 1998, pp 344-8.

[3] A. Marchioro, P. Moreira, T. Toifl, T. Vaaraniemi, "An integrated laser driver array for analogue data transmission in the LHC experiments", proceedings of the third workshop on electronics for LHC experiments, London, September 22-26, 1997, pp 282-6.

[4] F. Faccio, M. Campbell, K. Kloukinas, A. Marchioro, "An Amplifier with AGC for the 40MHz Optical Receiver of the CMS digital optical link", these proceedings.

[5] G. Cervelli, V. Arbet-Engels, K. Gill, R. Grabit, C. Mommaert, G. Stefanini, F. Vasey, "A method for the static characterisation of the CMS tracker analogue optical links", Technical note CMS Note 1998/043.

[6] K. Gill, V. Arbet-Engels, G. Cervelli, R. Grabit, C. Mommaert, G. Stefanini, J. Troska and F. Vasey, "Effect of Neutron Irradiation of MQW Lasers to 10^{15}n/cm^2", CERN CMS Experiment Technical Note 1997/044.

[7] K. Gill, C. Aguilar, V. Arbet-Engels, C. Azevedo, J. Batten, G. Cervelli, R. Grabit, F. Jensen, C. Mommaert, J. Troska, F. Vasey, "Comparative study of radiation hardness of optoelectronic components for the CMS tracker optical links", proceedings of the fourth workshop on electronics for LHC experiments, Rome, September 21-25, 1998, pp 96-9.

[8] J. Troska, J. Batten, K. Gill, F. Vasey, "Radiation effects in commercial off-the-shelf single-mode optical fibres", proceedings of the SPIE, Vol. 3440, 1998, pp 112-9.

[9] J. Batten, K. Gill, J. Troska, F. Vasey, "Radiation tolerance of MT multi-way single mode fibre-optic connectors to gamma and neutron irradiation", Workshop record of the data workshop, RADECS conference on radiations and their effects on devices and systems, Cannes, Sept 17, 1997, pp 75-80.

[10] J. Troska, K. Gill, R. Grabit, F. Vasey, "Neutron, proton and gamma radiation effects in candidate InGaAs pin photodiodes for the CMS tracker optical links", Technical note CMS Note 1997/102.

[11] F. R. Nash, "Estimating device reliability: assessment of credibility", Kluwer Academic Publishers, Massachusetts, 1993.