A 4-channel parallel analogue optical link for the CMS-Tracker

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Abstract

A radiation-hard, 4-channel wide parallel optical link has been developed for the analogue readout of the CMS-tracker detector. It is based on edge-emitting laser transmitters and pin photodiodes aligned to single-mode fibres on Si-submounts and housed in custom developed 4-way ceramic packages. The operating wavelength is 1310nm. Experimental results obtained with prototypes closely resembling the final system are presented. Measurements of dynamic range, linearity and bandwidth are shown, together with first results of inter-channel crosstalk. The resistance of the laser transmitter module to neutron irradiation is also reviewed.

1. INTRODUCTION

A radiation-hard, 4-channel wide parallel optical link has been developed for the analogue readout of the CMS-tracker detector (Fig. 1). It consists of a monolithic quad-laser driver ASIC followed by a hybrid assembly of 4 InGaAsP/InP edge emitting lasers housed in one single custom-developed low-mass, non-magnetic package. Single-mode optical fibre ribbons transmit the light at a wavelength of λ~1310nm over a distance of approximately 110m, through 3 patch panels based on angle-polished MT-connectors. On the receiver side, four InGaAs/InP pin photodiodes housed in a package identical to the laser module are followed by 2-stage transimpedance amplifiers based on commercially available, single-channel discrete ICs. Altogether, about 50000 optical links will be required to read-out the CMS tracker.

Results of performance and radiation hardness tests of individual components and single-channel optical links have been previously published [1]. This paper reports for the first time on the performance of a full length 4-channel parallel link, which closely resembles the final CMS-tracker optical readout system. Static and dynamic performance of the complete link are presented in section 2, together with first results of inter-channel crosstalk. The resistance of the laser module to neutron irradiation is briefly reviewed in section 3, while the evolution path towards the final system is sketched in section 4.

2. LINK PERFORMANCE

2.1 Link under test

Most of the components used to build the parallel optical link have been described previously [2,3,4] and single channel link demonstrators have been characterised and distributed to the CMS community [5, 6]. However, it is the availability of a 4-way package, custom developed by Italtel Milano [7] which has made this more realistic evaluation possible.

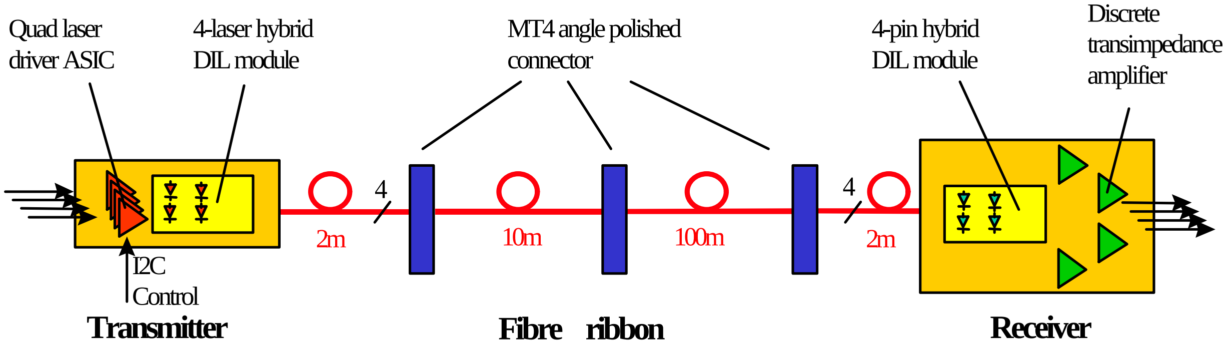

Fig. 1. 4-channel parallel analogue optical link prototype

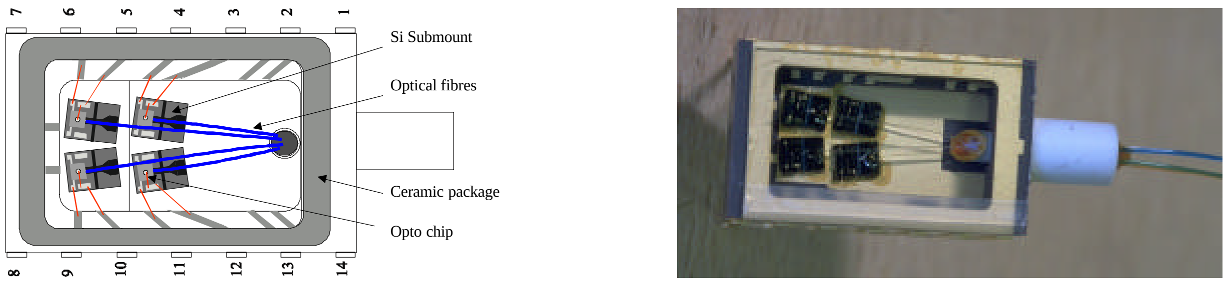

Fig. 2. 4-way Rx module internal configuration

The Italtel 14-pin ceramic DIL package houses up to four (known good) laser or photodiode assemblies in a volume of approximately 15mm x 10mm x 4mm. With the exception of the leadframe (still to be optimised), it contains no metallic parts and is thus low-mass and non magnetic. A bundle of 4 standard telecom-grade single-mode fibres exit the package through a ceramic ferrule, and are terminated by an angle polished MPO connector. Three pairs of 4-way transmitters and 4-way receivers have been tested. The lasers have an average threshold current of 10.3mA and a slope efficiency of 0.059W/A at 25°C, while the photodiodes have an average responsivity of 0.93A/W. A diagram and photograph of an open 4-channel receiver are shown in Fig. 2.

The working point and operating range of the tested links have been set to closely match the system specifications [8]: a laser driver transconductance of approximately 6.3mS converts the full range input swing of ±400mV into a laser optical output signal of approximately 300µW amplitude. This signal corresponds on the receiver side to an output swing of almost 4.2V into a high impedance load. If one includes 2dB of optical loss for the three in-line patch panels, the output swing becomes 2.65V, or 1.33V into a 50Ω load.

2.2 *Experimental set-up*

The experimental setup used to characterise the parallel optical link is shown in Fig. 3. It consists of pairs of generating and measuring instruments linked via GPIB to a computer running labview software. For the static characterisation, an arbitrary waveform generator and an oscilloscope are used; the dynamic characterisation is performed with a tracking generator coupled to a spectrum analyser; a pulse generator, together with an oscilloscope, are used to evaluate crosstalk. For high resolution measurements such as linearity, a 12bit A to D converter on a VME board is used. Also hooked on the VME bus is an I^2C interface board which controls the laser driver and allows individual setting and adjustment of the lasers working points. The I^2C bus remains idle during link measurements.

The laser driver ASIC features differential inputs. However, to ease the interface with laboratory instruments, only one input is active in this test, while the other one remains grounded.

On the receiving side, all outputs are terminated with 50Ω to ground, resulting in a 50% reduction of link net gain. It has been experimentally demonstrated that when integrating the receiving amplifiers close to the A to D converters on the Front End Drivers, this termination can be removed, thus eventually allowing to recover the full gain of the readout chain.

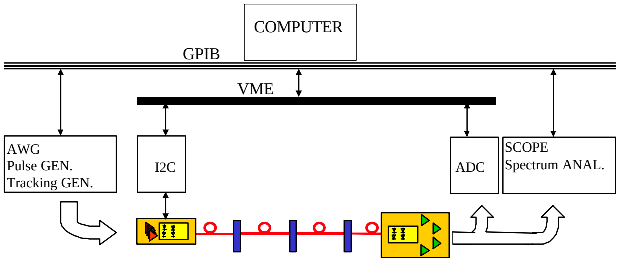

Fig. 3. Experimental setup for link performance evaluation

2.3 *Static characterisation*

The measurement procedure of the optical link static transfer characteristic consists in scanning the laser driver input voltage and, for about 100 input points, measuring the DC value and standard deviation of the receiver output voltage

The static transfer characteristics of the 12 tested optical channels are shown in Fig. 4 for an input voltage range slightly exceeding the nominal value of ±400mV. The kink at very low input voltages is due to the laser being operated below threshold. Even though this could be easily avoided by adjusting the laser bias point, it is useful in the characterisation phase to have an absolute reference point indicating the operating conditions of the system. The measured link gains (outputs terminated with 50Ω resistors) range from 0.98 to 1.7 V/V, with an average value of 1.2 V/V. This spread is essentially caused by the inhomogeneity in the insertion losses of the three in-line connectors.

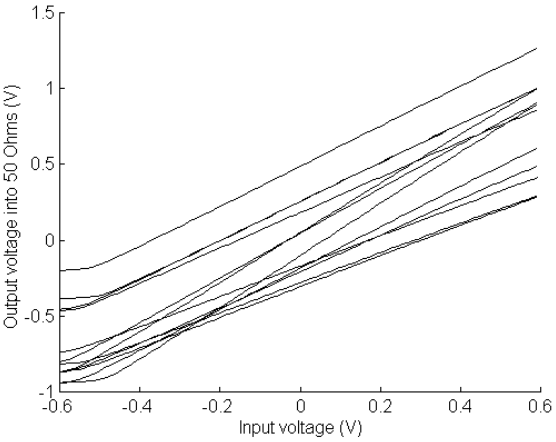

Fig. 4. Optical link static transfer characteristics

For each static measurement point, the standard deviation of the output voltage is also measured. The resulting noise characteristics are shown in Fig. 5 as a function of input voltage for the 12 tested channels. The bandwidth of the measuring oscilloscope largely exceeds that of the optical link (~120MHz, see section 2.5) so that the values shown truly represent the link rms noise. Since different channels have different gains, it is difficult to precisely compare noise figures at this point. A signal to noise ratio calculation is described in the following section.

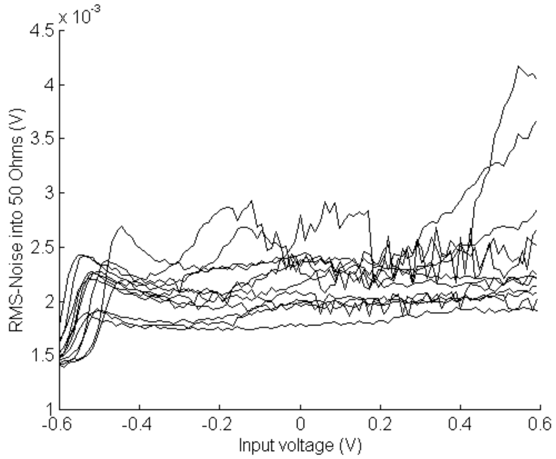

Fig. 5. Optical link output noise characteristics

2.4 Linearity and dynamic range evaluation

Based on the static characterisation data presented above, the analogue optical link performance is evaluated off-line with the method described in [9]: a working point is chosen above threshold and the signals sent through the link are modelled as pulses superimposed to this DC working point. In the present analysis, a working point of -0.4V has been chosen for all input channels.

To evaluate the system linearity, a regression line is drawn between the working point and a calibration point selected on the static transfer characteristic, within the operating range of the link. The relative deviation from linearity is defined as the normalised error between the output signals extracted from the transfer characteristic and those predicted by the regression line. In the present evaluation, the calibration point has been chosen to be 250mV above the working point (input voltage = -0.15V) for all channels. The calculated relative deviation from linearity is plotted in Fig. 6 as a function of input voltage. It is zero at the calibration point, and practically does not exceed 2.5% in the link full operating range. This figure is however dependent on the specific choice of the calibration point, and has not been finely optimised in this example. Around the working point (X_{work}=-0.4V), the relative deviation from linearity diverges as the signal reaches zero. Below the working point, the linearity is degraded by the laser approaching threshold; above the working point, it is essentially determined by the laser driver static transfer characteristic.

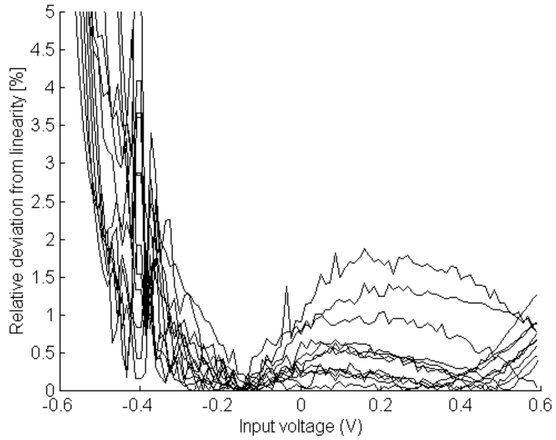

Fig. 6. Relative deviation from linearity computed from data in Fig. 4 (X_{work}=-0.4V, ΔX_{cal}=250mV)

The system signal to noise ratio is obtained by dividing the output signal (extracted from the static transfer characteristic) by the output noise (from the output noise characteristic). As can be seen in Fig. 7, peak signal to noise ratios in excess of 350:1 are achieved for all measured channels (at X_{peak}=+400mV), with the best link reaching a value close to 600:1. As was the case for the deviation from linearity analysis, the signal to noise ratios shown here are dependent on choice of working point, and could be further optimised on a channel by channel basis.

In order to assess the impact of the optical link on the total noise of the CMS-tracker readout chain, one must map the output range of the front-end chip into the input range of the optical link. Assuming an 8MIP dynamic range would correspond to the 800mV input range of the system described here, then the equivalent input noise generated by the optical link would for instance be less than 0.023MIPs for all channels.

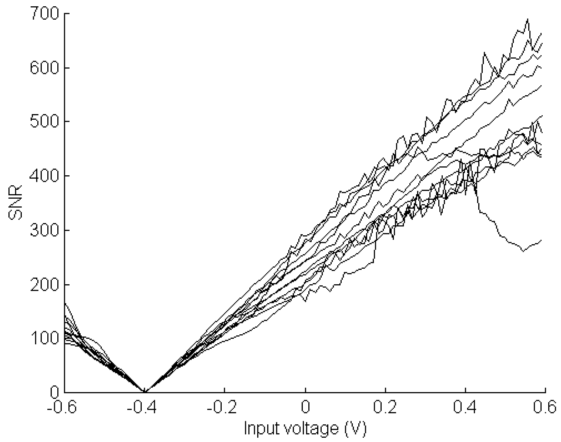

Fig. 7. Signal to noise ratio computed from data in figures 4 and 5 (X_{work}=-0.4V)

2.5 Dynamic characterisation

The optical link bandwidth is essentially limited by the receiving electronics. The frequency transfer function, as measured for one pair of 4-way modules is plotted in Fig. 8. It features a flat response with a -3dB bandwidth of about 120MHz. In the time domain, this value would correspond to a settling time shorter than 10ns [2].

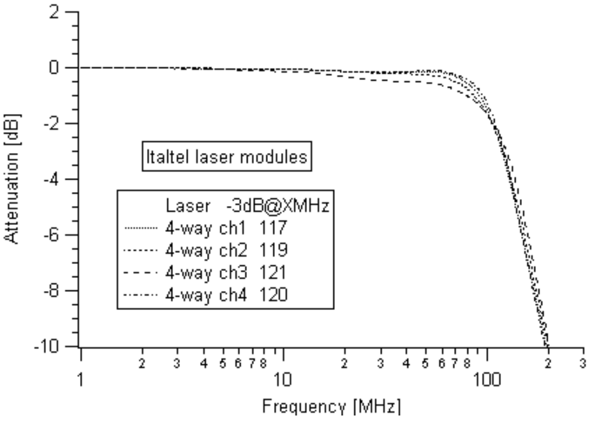

Fig. 8. Optical link frequency transfer function

In the final readout system, the optical link bandwidth will have to be optimised, together with the front-end and back-end responses, so as to minimise the amount of noise induced for a given readout system speed.

Due to the pulsed nature of the signal transfer scheme used for the CMS tracker, the crosstalk (or relative feedthrough from one channel to its neighbour) is defined at sampling time t_s≥20ns for a step input injected at t=0s. Even though some feedthrough is apparent during the few nanoseconds after the step edge, very little effect remains visible after 20ns. We measure typical crosstalk values of about -63dB, in no cases exceeding -55dB.

2.6 Summary of test measurements

We compare in Table 1 the results presented in this section with the system specifications [8]. The 12 tested prototype channels all meet the objectives of the CMS tracker readout system.

3. RADIATION HARDNESS

With the exception of the laser-driver ASIC, which is still integrated in a radiation-soft technology, all opto-electronic front-end components have been validated for radiation hardness. Single-channel laser-transmitters [10], standard telecom-grade optical fibres [11] and multi-way MT connectors [12] have shown good resistance to levels in excess of the CMS-tracker requirements. Figure 9 shows the normalised degradation of laser threshold current and efficiency as a function of neutron fluence for a 4-channel module. As expected, the results are similar to the ones obtained with single channel devices. Fluences (integrated over the lifetime of the CMS experiment) to be expected at the innermost Si-tracker layers are ~10^{14}neutrons/cm^2 (1MeV) and 1.6x10^{14} charged hadrons/cm^2 [13] (mainly charged pions, 10^2 - 10^4 MeV, found to be almost 4 times more damaging than neutrons (6MeV) [10]).

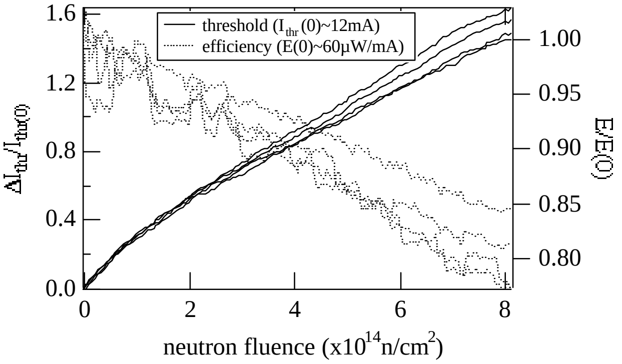

Fig. 9. Degradation of a 4-channel laser module irradiated with 6MeV neutrons (annealing behaviour not shown)

Table 1. Comparison of specified [8] and measured optical link performance

		Specified			Measured		
#	specification	min	typ	max		unit	note
2.1	Length	60	100	120	114	m	
2.2	Gain	1.4	2.85	5.7	2.4	V/V	Into high impedance
2.3	Peak signal to noise ratio		48		>50.9	dB	
2.4	Relative linearity deviation			2.5	<2.5	%	in output range
2.5	Bandwidth		70		120	MHz	DC coupled
2.6	Settling time			18	<10	ns	
2.9	Crosstalk		-48		<-55	dB	$t_s \geq 20$ns

4. CONCLUSION

With the demonstration of a functional and radiation-hard 4-channel parallel analogue optical link, the baseline for the CMS-tracker optical readout system is set:

♦ Assemblies of edge-emitting lasers, pin photodiodes and optical fibres on silicon submounts are the basic building blocks of the optical link transmitters and receivers. They can be individually tested for performance and radiation hardness, packaged into one-way or multi-way housings, or possibly even assembled directly onto hybrids or printed circuit boards. This flexibility in the packaging scheme allows testing and validation of opto-electronic components in submount form before the full details of the system architecture and implementation are known, and before a final package or hybrid has been selected and designed.

♦ Standard telecom-grade single mode fibre ribbons link front-end to back-end. They are connected in three points with MT-compatible connectors to ease installation, test and maintenance of the detector.

Three 4-way parallel analogue optical links closely resembling the final CMS system have demonstrated a performance complying with the specifications. The custom developed 4-way package used both for the transmitter and receiver modules has been successfully tested for mechanical robustness [7], and will be subjected to magnetic field tests in the coming months. Irradiated and non-irradiated lasers and pins are currently undergoing accelerated ageing tests. Up to this day, no significant degradation effects have been observed in more than 1200 hours of operation at 80°C.

Work is in progress to better adapt the link modularity and density to the needs of the CMS tracker. In particular, projects with industrial partners have been launched to increase the density of the optical patch-panel, multi-ribbon cable and receiver modules.

5. REFERENCES

[1] F. Vasey, V. Arbet-Engels, J. Batten, G. Cervelli, K. Gill, R. Grabit, C. Mommaert, G. Stefanini, J. Troska, "Development of radiation-hard optical links for the CMS tracker at CERN", IEEE transactions on nuclear science, Vol. 45, No. 3, pp. 331-7, 1998.

[2] V. Arbet-Engels, G. Cervelli, K. Gill, R. Grabit, C. Mommaert, P. Moreira, G. Stefanini, F. Vasey, 4 papers published in proceedings of the third workshop on electronics for LHC experiments, CERN/LHCC/97-60, pp. 270-298, 1997.

[3] G. Chiaretti, "Optical link technology: silicon optical bench technology", proceedings of the third workshop on electronics for LHC experiments, CERN/LHCC/97-60, pp. 115-119, 1997.

[4] 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, CERN/LHCC/97-60, pp 282-286, 1997.

[5] V. Arbet-Engels, G. Cervelli, K. Gill, R. Grabit, C. Mommaert, G. Stefanini, F. Vasey, "Analogue optical links for the CMS tracker readout system", Nuclear instruments and methods in physics research A409, pp. 634-8, 1998.

[6] Report on the tracker readout milestone, CMS tracker technical design report, CERN/LHCC 98-6, pp. 319-23, 1998.

[7] M.Magliocco, P. Nugent, "Four channel fibre optic transmitter and receiver modules for CMS detector tracker readout links", these proceedings.

[8] F. Vasey, "CMS tracker optical readout link specification", Vers. 2.1, June 17, 1998. Available on:http//www.cern.ch/CERN/Divisions/ECP/CME/OpticalLinks/

[9] 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.

[10] K. Gill, V. Arbet-Engels, G. Cervelli, R. Grabit, C. Mommaert, G. Stefanini, J. Troska, F. Vasey, "Pion damage in semiconductor lasers", Technical note CMS Note 1998/046.

[11] 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 (in print), 1998.

[12] 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.

[13] Report on the tracker radiation environment, CMS tracker technical design report, CERN/LHCC 98-6, pp. A1-A22, 1998.