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Status Report on the RD-23 Project

Optoelectronic Analogue Signal Transfer for LHC Detectors

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1. Introduction

This is the 3rd status report of RD23, the two previous ones [1, 2] having been submitted in September 1993 and October 1994, respectively. The aim of the project is to develop point-to-point fibreoptic links for transferring signals from the front-end electronics to the back-end readout in LHC detectors. The distinctive technical feature of this project is that electro-optic semiconductor reflective modulators are retained as the baseline choice for front-end transmitters. The main goals are:

- the development of rad-hard, low-power modulator arrays;
- the development of hybrid transceiver arrays (lasers, couplers, photodiodes), to be mounted on readout modules at the back-end of the link;
- the link performance evaluation, in the lab and in beam tests with particle detectors;
- the experimental study of the radiation hardness of fibres and multi-way optical connectors.

A substantial effort has also been invested in the development of prototype readout modules.

The links are mainly intended for the transfer of analogue signals from the analogue pipelines in the tracker front-ends. However, they can equally well be used for digital data transmission.

The functional block diagram of the reflective link is schematically shown in Fig.1. The electro-optic modulator transmitters, mounted on (or close to) the front-end detector hybrids, convert the pipeline sampled voltages into optical signals by modulating continuous-wave (CW) light from laser diodes coupled via optical fibres. The reflected modulated optical signals are converted back to electrical in transceivers on the readout modules at the back-end. The transceivers are opto-hybrid devices and include lasers, couplers, photodiodes and receiver pre-amplifiers. The incoming CW laser power and the reflected modulated signal are carried by the same fibre.

The modulator development work has been focused on Asymmetric Fabry Perot Modulators (AFPM). These are reflective devices operated by tuning the electro-absorption properties of InGaAs/InP multi-quantum-wells (MQW). They are polarisation insensitive, and their vertical structure allows the fabrication of very dense arrays. A reflective link based on AFPMs requires only one input/output fibre directly coupled to the modulator chip in a very compact package.

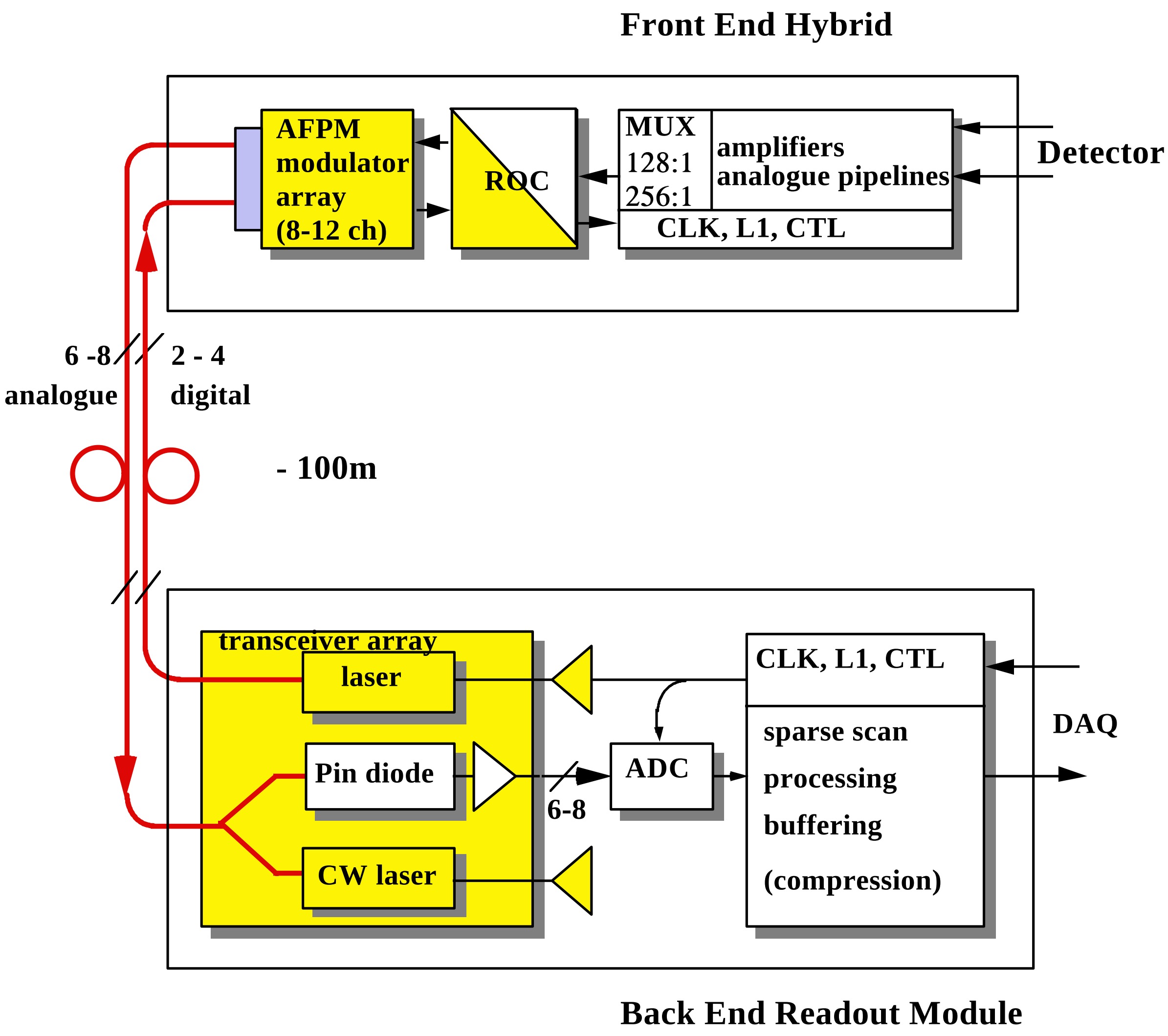


Fig. 1 - Functional block diagram of the reflective optical link

The analogue readout based on the RD23 developments is currently the baseline choice for the CMS tracker [3] and is being actively evaluated in ATLAS [4].

2. Project management in 1995

In this last year, the project has been confronted with several strategic decisions on the choice of industrial partners and technologies. A brief account is given in this chapter, while a full report of technical activities is given in the following chapters.

2.1 Industrial partnership - HEP participants

In 1994, the RD23 collaboration included eight academic institutions and one industrial partner (GEC-Marconi Defence Systems (GMDS)). Since the inception of this project, GMDS had taken responsibility for managing and subcontracting the industrial developments for modulators, in particular with GEC-Marconi Materials Technology (GMMT), where most of the modulator developments are carried out. GMDS were committed to match the RD23 common fund for industrial programmes on a 1:1 basis. The partners in the HEP Institutes were responsible for evaluating the devices delivered by industry.

Early in 1995, GMDS (a system company) decided that, particularly in view of the relatively long timescale of the project, they could not expect a satisfactory return from their investment in component developments (mainly with GMMT), unless they were assured that the production of a substantial share of the whole readout system (including modules and power crates) would eventually be contracted to them. It was obviously impossible to take such a commitment, and GMDS decided to withdraw from the project. The event was not totally unexpected and provisions had been made to assure continuity. CERN has taken full responsibility for project management. However, the GMDS matching funds for 1995 were lost and time had to be invested to establish a working relationship and re-negotiate development contracts with industry (including intellectual property rights). The AFPM development programme with GMMT suffered some delay but was successfully re-confirmed in Aug. 1995.

The list of HEP Institutes now includes a group of participants from the INFN section and the Electronics Engineering Dept. of the University of Perugia (I), who have joined the RD23 collaboration in Sept. 1995. They plan to focus their contribution in the development of the drivers for the AFPMs on the front-end hybrids for the CMS tracker.

2.2 Technical activity

Following the previous status report in Nov. 1994, the DRDC set the following milestones for 1995:

- Produce and characterise MQW modulators in a package convenient for LHC needs, in a quantity sufficient to assess the fabrication process and the yield.
- Study the integrated and hybrid transceivers. Choose between these two options and build a prototype.

We recall that most of the results with MQW AFPM modulators reported in 1994 had been obtained with devices based on phase 1 chip design (1992) in a prototype package relying on actively aligned micro-lenses to couple the light between chip and fibre. Four 4-channel micro lens coupled assemblies were available in 1994. This package was rather complex and showed an excessive sensitivity to temperature changes.

The results reported here have been obtained (unless specified) with devices based on phase 2 chip design (1994) in a compact package in which fibre and chip substrate are directly butt-coupled. The package dimensions for a 4-channel array are: footprint Å 6.5x3.5 mm^2, height Å 4 mm (the width of the package would increase slightly for an 8-channel array). Two 4-channel butt-coupled units had been delivered as advanced prototypes in Sept. 94, and 11 additional units have been made available in 1995. The successful development of the miniature package, with good thermal stability, is a significant step towards the demonstration of the feasibility of the link. The performance evaluation of all the units is reported in sect. 5.2.

Measurements have been carried out to assess the capabilities of modulators in digital transmission. Preliminary results are reported in sect. 6.

A programme for the design and growth of MQW wafers is ready to be started with the Interdisciplinary Research Centre for Semiconductor Materials (IRCS) in Oxford. The main goal of this programme is to provide second-sourcing of AFPM chips for lab tests and to investigate alternative chip design and wavelengths. However, it would not be realistic to envisage large-scale production with the required homogeneity at IRCS. The effort to identify an industrial grower with adequate volume production capabilities is under way and we are confident that this issue will be clarified in 1996.

We have continued the development and assembly of discrete component transceivers, to be used in lab and beam tests with front-end chip prototypes. The 4 channel analogue readout modules used in 1994 and 1995 are very similar. The 1995 units (see Fig. 4) feature lower electrical noise (1.8pA/ÃHz), higher bandwidth (100MHz) and higher transimpedance gain (1M½) than their predecessors. The assembly of the passive waveguide components has been successfully transferred to industry. Five 4-channel units have been built in 1995, four of which are now being used outside CERN.

Substantial progress has been made in the feasibility study of an integrated miniature transceiver. Following a careful market survey and technical evaluation, we have established an industrial partnership with ITALTEL Photonics Components Division (Milano), which offer an advanced glass-on-silicon technology. A programme to develop opto-hybrid transceiver arrays has been started in May 1995. Prototypes will be delivered in Nov. 1995.

The study of radiation effects (gamma rays) on modulators and fibres has been pursued and extended to the case of lower dose rates, corresponding more closely to the expected conditions in the LHC detectors. In 1994, various types of single-mode fibres had been exposed to ^{60}Co γ rays at a high dose rate (dD/dt Å 200krad/h) for an integrated dose

D>20Mrad. From these measurements and using a kinetic model, the predicted induced attenuation in LHC like conditions was ÆA~0.5dB/100m/year for pure silica core fibres. The same types of fibres have been irradiated in 1995 at a dose rate (dD/dt Å 780 rad/h) close to the one expected at the LHC. The new results point to an induced attenuation ÆA Å 1.5dB/100m/year in these conditions.

The investigation of system issues has been pursued to assess various constraints and requirements, including those that are detector dependent: array modularity, optical connectors, reliability, etc.

3. Progress report on AFPM transmitter developments

In this chapter we report the progress achieved on AFPM chip modelling and device packaging. We also report on the characterisation of modulators as photodectors; this mode of operation offers a very attractive solution for the implementation of bi-directional links.

It should be pointed out that the overall performance of the system can best be measured on a complete link, as it is affected by interactions of the individual components that may be difficult to predict and unfold. System performance is reviewed in sect. 5, where most experimental results are presented.

3.1 AFPM chip

The results of phase 2 wafer growth at GMMT fell short of the expectations. The efficiency of the modulator chips is on the average 2x lower than in phase 1 devices. Experimental investigations have shown that the reduced performance is not due to the mirrors nor to residual cap layers. From the device model, it is likely that the slight reduction in well thickness, adopted in this growth to match the wavelength requirements, has caused a broadening of the MQW absorption edge, leading to a reduced absorption change and hence a reduced reflection change as a function of applied voltage.

It had been planned initially to produce a substantial number of devices for evaluation with phase 2 parameters in the butt-coupled package, in order to meet the milestone set last year. However, following the disappointing phase 2 result, priority in the 1995 development programme with GMMT was given to grow structures with phase 1 parameters and new masks for 8-channel devices. The start of this programme suffered a significant delay following changes in the management of the project. The wafer growth is currently under way and the delivery of 30 off 8-channel modulator chips based on phase 1 design parameters is due in Jan. 1996. The packaging development programme has been postponed and will be resumed as soon as the new chips will have been delivered and evaluated.

3.1.1 *Toleranced model*

Considerable effort has been invested by GMMT in the development of a new AFPM design tolerancing programme based on Monte-Carlo sampling of the design parameter space. The modelled device performance (in general the maximum linear reflectance change) is mapped around a given starting specification, subjecting the layer thicknesses to random variations. This allows the designer to set the growth specifications so that the effects of process tolerances on chip performance are minimised.

This method has been applied for validation to the analysis of the phase 2 design, which had resulted in lower than expected performance. The results show indeed that the quantum well width chosen (58Å) is not centered in the region of best performance but very close to an edge with steep drop in modulation efficiency. The model will be used to determine the most favourable design parameters in future growths.

3.1.2 *Wafer screening criteria.*

The two mirrors forming the AFPM cavity are an epitaxially grown low reflectivity Bragg structure and a high reflectivity gold mirror deposited after growth. This structure avoids the difficulty of growing a high reflectivity InP based Bragg mirror, but makes the post-growth evaluation of the wafers difficult as the modulator cavity is complete and testable only at the end of the processing sequence. The screening procedure of the as grown wafers is thus based on measurements of an uncomplete cavity, with the risk of accepting and processing defective wafers. Significant effort has been put into selecting screening criteria that have a well defined relationship to the expected performance of a processed device .

3.1.3 *Optical reflectivity test bench*

For the reasons explained in the previous sections, it has been found appropriate to decouple structure growth and chip development from packaging issues. This means that modulator arrays delivered by industry must be evaluated already in chip form. The laboratory characterisation of unpackaged AFPM chips as a function of wavelength and voltage requires installing an optical reflectivity measurement setup with a fine coverage of the operating spectral bandwidth. Test benches are now operational at CERN and at Siegen. The CERN set up has allowed to cross-check the measurements reported by

GMMT on phase 1 (1992) growth, and will be used to evaluate the new chips to be delivered by GMMT and IRCS in 1996.

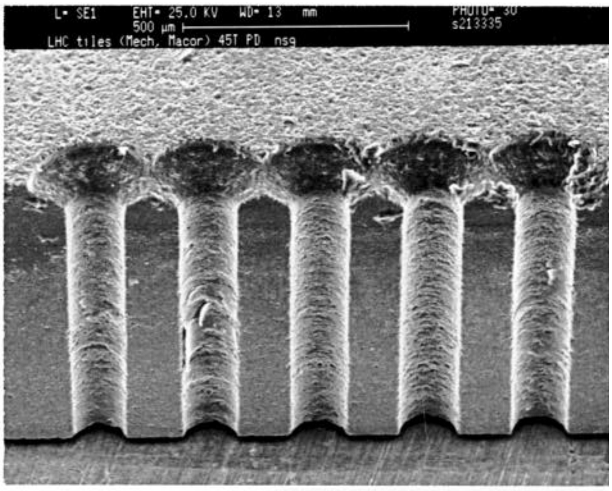
3.2 AFPM package

A package based on passive alignment for fibre ribbon termination has been developed by GMMT [5]. The fibres are constrained in precision holes drilled with tight tolerances in a ceramic substrate. Since the AFPM chips are optically accessed from the substrate side of the device (thickness t Å100µm), light losses may be significant if the angular alignment of fibres is not well controlled.

Various substrates and micromachining techniques have been evaluated for drilling arrays of holes (fibres cladding outer diameter 125µm, pitch 250µm) with the required alignment accuracy (within Å 2_ of the axis normal to the substrate). Key issues are hole positioning, diameter and roundness control, taper, freedom from debris or redeposited material and substrate compatibility for thin film photolithography and flip-chip solder bond assembly. A fibre entry lead-in was also desirable for easy assembly.

The best results were obtained with 0.025" thick ceramic substrates using either a copper vapour laser with a trepanning technique or a precision mechanical drill fitted with a tungsten carbide drill bit (see Fig. 2.a). An additional hole was included to provide pressure relief while gluing the fibres to the chip.

Plates with a matrix of 6.5 x 4 mm^2 tiles were photolithographically patterned with wettable metal pads aligned to the holes, lead/tin solder and gold electrical connection tracks before dicing. The InP modulator chips were flip-chip solder bonded onto individual alumina tiles prior to attachment of a flexible lead frame and fixing of a lid. Solder bonding provided only a mechanical connection, wire bonds on the chip superstrate were used for electrical connections. The 4-way fibre ribbon ends were stripped, cleaved and inserted into the hole array (see Fig. 2.b). A UV-curing adhesive provided a refractive index match to silica and a mechanical bond to the tile. The package volume is 6.5 x 4 x 3.2 mm^3 excluding electrical connections and fibre strain relief boot. Insertion loss is as low as 2.3dB round trip. Preliminary environmental tests indicate that this value should not vary by more than 0.5dB over a ±5 °C temperature range.


L= SE1
EHT= 25.0 KV
WD= 13 mm
PHOTO= 30
500 µm
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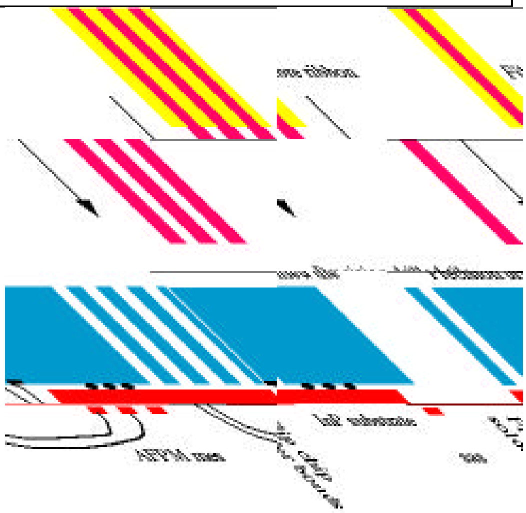
LHC tiles (Mech. Macor) 45T PD nsg

a)



b)

Fig. 2 a) SEM micrograph of sectioned mechanically drilled and countersunk 125µm diameter hole array. b) Modulator array termination with fibre array passively aligned laterally and angularly.

3.3 AFPM as photodetector

The possibility to partition monolithic arrays of AFPMs into modulators and detectors is attractive from a system point of view. The estimated average AFPM detection efficiency of η Å 0.3A/W should be compared to a value of η Å 0.8A/W for commercially available InP photodiodes. A typical AFPM chip photoabsorption spectrum is shown in Fig.3a. In the operating region around the 1.55µm wavelength, the detection efficiency of the modulator, used as photodetector, is critically dependent on wavelength and bias, reaching a maximum of η Å 0.32A/W on the excitonic peak. In the 1.3µm window however, the AFPM operates like a conventional photodetector. The detection efficiency measured in this window with micro-lens coupled phase 1 design chips is η Å 0.25A/W (Fig. 3b). This value depends on package insertion loss.

a

Fig. 3 a) Photocurrent spectrum measured at chip level (phase 1 design) for bias voltage V=0V (left peak),-2,-4,-6,-8,-10 (right peak),-14V. b) Photocurrent characteristics of packaged AFPM (micro lens coupled) at λ Å 1.3µm

Crosstalk is a potential concern when a modulator channel (with an input voltage drive up to Å 3V pp) is adjacent to a photodetector channel with a few µA input current signal. Preliminary measurements indicate that a sine wave of frequency f Å 10MHz and amplitude ΔV Å 3Vpp applied to a modulator channel induces a ripple ΔI Å 3µA on an adjacent detector channel. This crosstalk is dominated by capacitive coupling along the electrical signal tracks. Considering that only digital information needs to be received, a comfortable -20dB crosstalk margin would thus be achieved for photodetector signal powers in excess of 100µW. This measurement needs to be validated with butt-coupled packages and with analogue signals matching the 40Msamples/s specification.

4. Progress report on transceiver developments

The transceiver module performs all electro-optic conversion functions at the link back-end: it generates the CW laser power sent to the modulators, detects and amplifies the back reflected analogue signals and transmits the digital timing trigger and control information to the front-end. The transceiver block diagram is shown in Fig. 4.

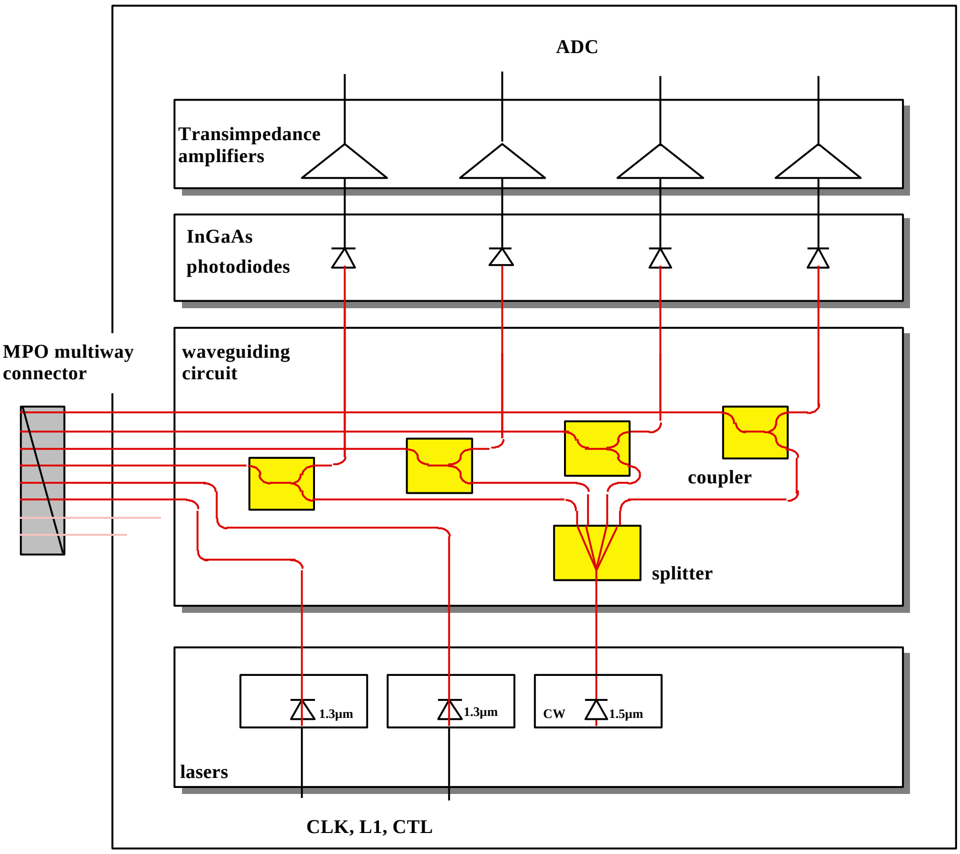


Fig. 4. Transceiver functional block diagram. The number of channels should be dimensioned to suit the MPO connector modularity (4,8 or 12 ways)

4.1 Discrete transceiver

So far, all optical link measurements have been carried out with transceivers assembled using discrete, commercially available optical components (pigtailed laser diodes and photodiodes, splitters and couplers in the form of fused-fibre or integrated waveguide devices). They do not include the two 1.3µm lasers shown in Fig. 4, as only analogue front-end data transmission has been investigated until now.

Several 4-channel passive modules have been assembled at CERN or procured from industry. Insertion loss from splitter input to MPO connector output is Å 12dB. Fibreoptic components are fusion spliced and assembled, together with active components, in a 6U VMEbus format module.

The CW laser serving the modulator channels is a high power device (PÅ 5mW coupled into the fibre @ λ Å 1540µm). Both Fabry Perot and Distributed Feed Back (DFB) types have been used, with a slightly improved noise performance for the latter option at the expense however of an optical isolator needed to prevent laser instability due to back-reflections. The photodiodes have high return loss (RL>40dB) to reduce phase to intensity optical noise conversion in the link.

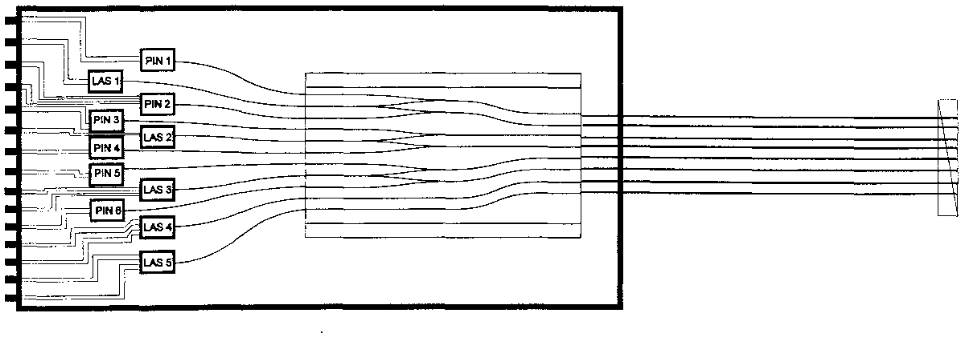
Low noise transimpedance amplifiers (I_nÅ1.8pA/ÃHz) followed by a differential gain stage have been designed and built. They assure an overall equivalent differential transresistance R_tÅ1M½ in a bandwidth BW Å 100MHz.

4.2 Opto-hybrid transceiver array

Transceivers based on discrete fibre optic components offer a satisfactory solution in systems with a small number of channels, but are too bulky and expensive to be used in LHC experiments. We have made a survey of the technologies currently available which would be suitable for miniaturisation and cost-effective volume production. Monolithic integration of photonic components is progressing but the required performance and the low target costs do not seem to be achievable on the required timescale. On the other hand, mature technologies exist for opto-hybrids; these consist of substrates on which waveguide structures are deposited and which are hybridised with active components. Opto-hybrids allow to achieve compact packages.

We have retained the glass-on-silicon technology developed by ITALTEL [6] to fabricate the passive waveguide structure. Design optimisation of splitters and couplers must take into account the trade-off between waveguide pattern complexity and number of lasers. Two configurations are currently being evaluated as shown in Fig. 5. In both cases, six analogue channels (receivers) and two timing trigger and control digital channels (transmitters) are implemented. The waveguide pattern is complex in the case of a 1 x 4 splitting ratio (Fig. 5.b), as crossing waveguides need to be implemented and crosstalk risks exist. To minimise those, the intersecting angle needs to be increased, leading to a larger chip size and thus a less compact package. The benefit is however a reduced number of lasers and fibre connections and an important intermediate feasibility demonstration if larger splitting ratios are to be envisaged.

The passive waveguiding circuits corresponding to the two configurations are currently being developed by ITALTEL. Prototypes are scheduled for delivery around end 1995 with substrate dimensions Å 10x30mm^2. In the 1996 programme we plan to hybridise photodiodes and preamplifiers on the submounts. The target footprint of the overall package is Å 20x60mm^2.


PIN 1
LAS 1
PIN 2
PIN 3
LAS 2
PIN 4
PIN 5
LAS 3
PIN 6
LAS 4
LAS 5

b

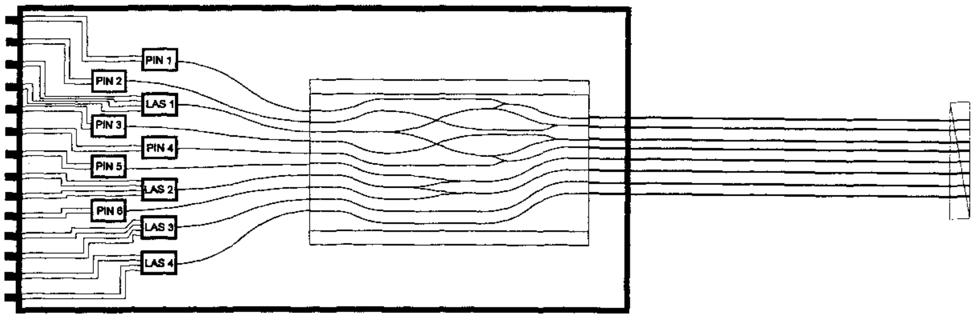


Fig. 5. Transceiver block diagram for 6 analogue and 2 digital channels. a) option based on 3 1x2 splitters. b) option based on one 1x4 and one 1x2 splitter for the 6 analogue channels.

5. Overall link performance (analogue mode)

The overall link performance is determined by the contributions of all individual components, including fibre patch cords and optical connectors. The results reported here were obtained with a 4-channel transceiver assembled with discrete fused fibre couplers. The photoreceiver gain was G_t Å 0.22V/µW (terminated into 50 ½) in a bandwidth B Å 30MHz. The link length (non rad-hard single mode fibre) varied between 10m and 20m, with two breakpoints based on FC-PC and MT-4 angle polished connectors. All modulators were 4 channel arrays passively aligned and butt coupled to fibre ribbons. Chips used in these packages had a 50% modulation efficiency reduction compared to devices issued from previous growths.

It may be useful to recall the electrical drive requirements for the modulators. The bias voltage corresponding to the centre of the linear range (bipolar signals) is V_b Å -10V. Assuming that the CW input optical power to the modulator is Å 100µW (at λ Å 1.54µm wavelength), the corresponding DC photocurrent would be I_{ph} Å 30µA. The driver is AC coupled to the modulator. The AFPM chip capacitance (excluding the lead frame) is C Å 1pF.

5.1 Evaluation criteria

The optical link performance is quantitatively evaluated by measuring its transfer function (back-end transceiver voltage output vs. front-end modulator voltage input), linearising it around its quadrature point and determining the linear range of operation for a ±1% maximum integral non-linearity deviation [1,2]. The slope of the linearising function is the link gain. The product of link gain and linear input range is the link modulation depth. The peak signal to noise ratio is the ratio of modulation depth over noise.

5.2 Uniformity of modulator channel characteristics

All phase 2 AFPMs delivered to date were tested on one single transceiver channel, as shown in Fig. 6a. The distributions of linear input range, bias voltage and link gain are shown in Fig. 6b, 6c and 6d, respectively. The spread in link gain is characteristic of an assembly technology which is not yet fully mature. It is determined by the package insertion loss (first iteration of the packaging development programme) and the connectors mating loss. The spread in AFPM bias and linear range may be ascribed to either cavity inhomogeneities at the chip level and/or more probably to external cavity effects at the package or system level. The chip development programme currently under way with GMMT will allow us to estimate the inhomogeneities at chip level with more confidence in 1996.

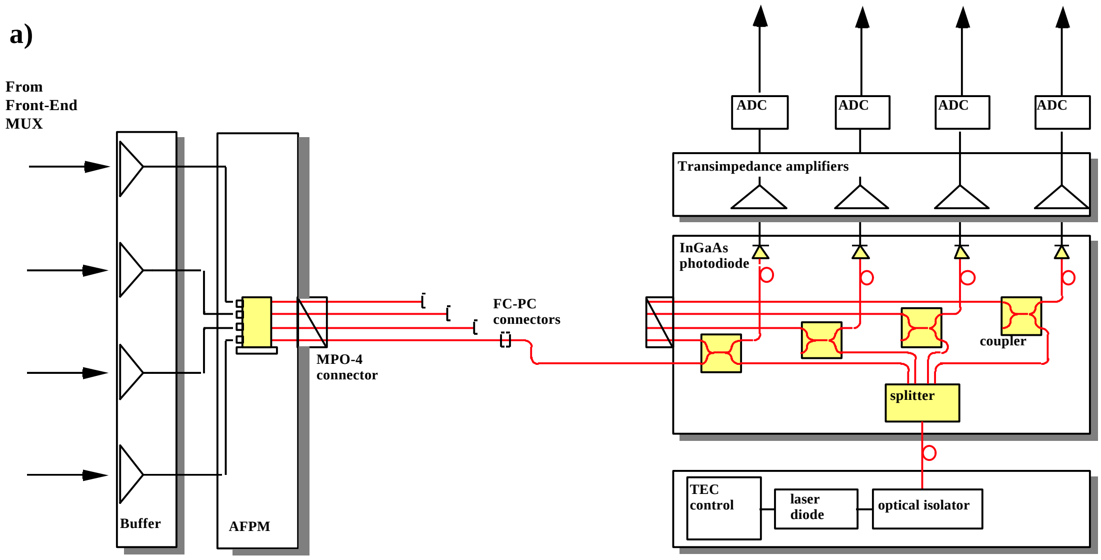


Fig. 6a - AFPM evaluation test setup

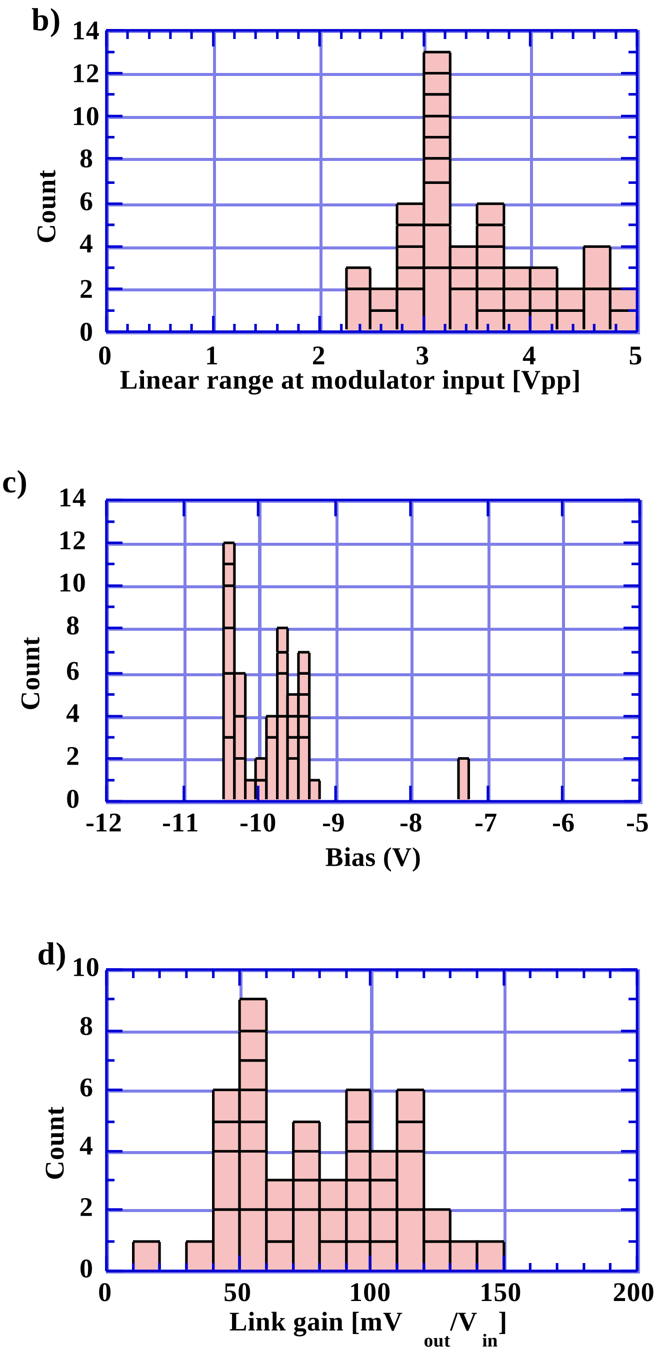


Fig. 6 (b, c, d). Comparative evaluation of 48 butt coupled AFPM channels. λ=1540nm, 85µW in fibre (see text)

For each optical channel, the product of linear input range and gain determines the peak signal level which can be transmitted within the accepted distortion limits. The rms noise level measured in a 30MHz bandwidth is σ Å 5.8mV rms. Fig. 7 shows the distribution of link gain and linear range measured on 48 optical channels against a 100:1 peak signal to rms noise ratio target. In plotting this target, we assume that the optical power (and hence the link gain) can be increased by a factor of 3 (to 250μW in the fibre) without degrading the noise level [2].

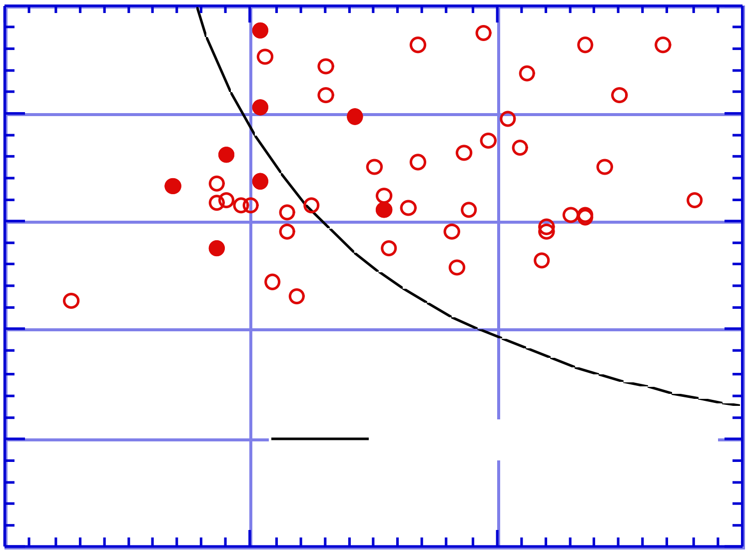


Fig. 7 - AFPM link gain and linear range distribution. Solid dots indicate the 1994 advanced delivery units.

At this early stage, over 70% of all functional channels meet a 100:1 signal to rms noise ratio target. It should be noted however that the noise figure assumes the use of an isolated DFB laser and that the signal levels were measured with low insertion loss FC/PC connectors at one of the two link breakpoints. Improvements are expected by refining the assembly process (better angular and positioning precision of the fibre guiding holes, better flip chip alignment) and systematically checking the connectors at the factory. The link gain will be improved by using chips of higher modulation efficiency (a factor of 2 is expected for the next iteration), and by decreasing the insertion loss of all optical components on the light path.

5.3 Beam tests

The optical link has been integrated into a complete readout chain (including front-end APV and FELIX electronics and data acquisition) by three independent groups during three ATLAS and CMS beam tests. The off-line data analysis is still under way and final results are not yet available. However, the on-line monitoring of data confirmed the results obtained in 1994 during the CMS beam tests [7]. The analogue link does not introduce any noticeable degradation of detector signal to noise ratio when compared to a copper link; noise is still largely dominated by the detector and front-end chip contributions. A few problems were observed and require further study. In the beam tests, where Sirocco readout modules were used, multiplexing was done at relatively low frequency (a few MHz) while the AC coupling time constants in the link amplifiers had been optimised for a substantially higher rate. Moreover, the overall link dynamic range was compressed by the need to accommodate the rather large pedestal level fluctuations generated by the front-end chips. A complete analysis of the results is in preparation [8,9].

6. Test of modulators for digital data transmission

A preliminary evaluation of the modulators for digital transmission has been done. The bit error rate (BER) at the receiver has been measured at different levels of CW optical power. The modulator was driven with a voltage swing of Å 2Vpp and a standard pseudo-random bit sequence was used with a clock rate of 100Mb/s. The results are shown in Fig. 8.

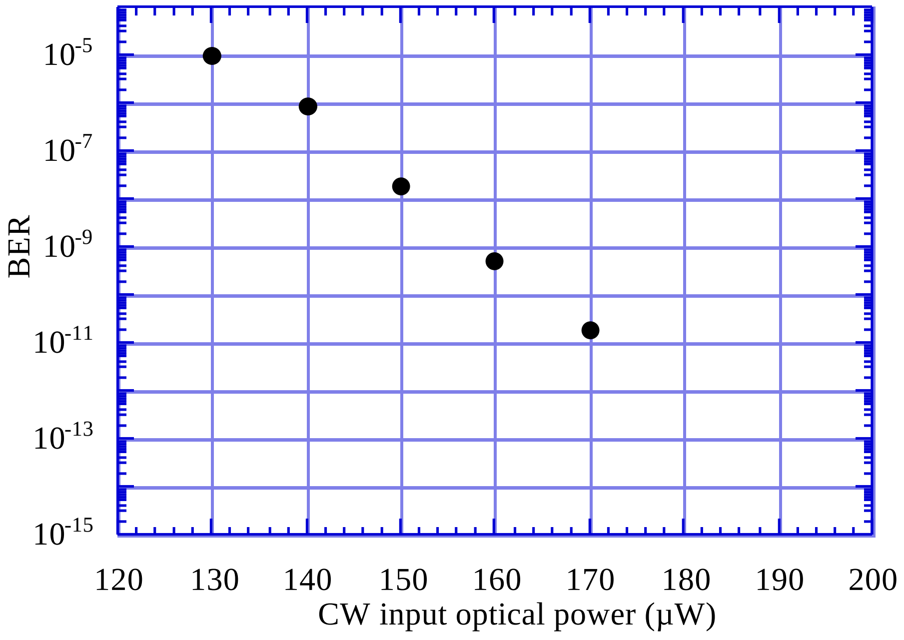


Fig. 8 - Bit error rate (BER) vs CW input optical power (100Mb/s clock)

The BER has a steep dependence on signal/noise ratio, which is roughly proportional to the CW optical power launched in the link. A BER Å 10^{-11} is achieved at Popt Å 170µW. The predicted BER for the more usual condition Popt Å 200µW would be BER Å 10^{-15}. The direct measurement of such low BER values is however time consuming and impractical.

It should be stressed that these results have been obtained with a receiver design which is not optimised for this application. The pre- and post-amplifiers were in fact the same as used for analogue characterisation, and their bandwidth limitation prevented operation at clock frequencies higher than Å 100MHz. More extensive measurements with optimised receivers are planned.

These first results show that efficient digital links can be implemented with MQW transmitters. We point out that the modulator used in this test (phase 2 design) had a relatively low efficiency (75mV/V gain 3.5Vpp linear input range, see Fig. 7). This confirms that even modulator channels with a performance that would be graded as poor for analogue applications can be used for digital transmission.

7. Irradiation of fibres and modulators

Systematic long-term measurements (more than 100 days at the time of writing) at low dose rate (dD/dt Å 600Rad/h at modulator site) are currently taking place at the Imperial College ^{60}Co γ ray irradiation facility. The total dose accumulated during the 3 months observation is Å 1Mrad. A software problem inhibited data recording during approximately 2 weeks around t=2000hr. The experimental setup is shown in Fig. 9.

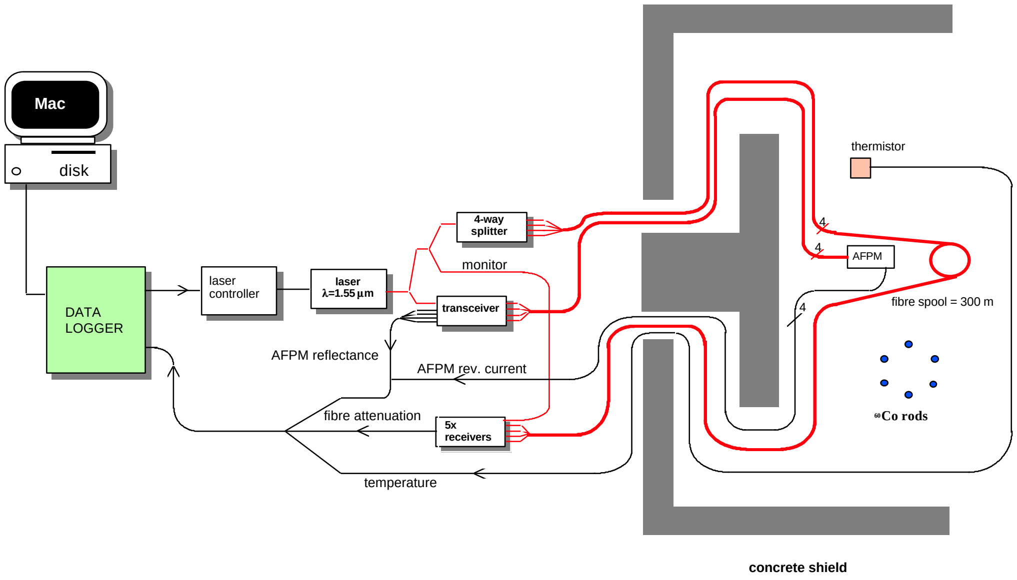


Fig. 9 - Experimental setup for ^{60}Co γ ray irradiation of fibres and modulators

7.1 Optical fibres

Extensive measurements on several types of fibres at high dose rates and neutron fluences have been reported and published [2,10,11]. The main aim of the present irradiation measurements is to determine the γ ray exposure induced attenuation in the same types of fibres, but this time at a dose rate dD/dt ~780 rad/h close to the value expected at LHC (dD/dt ~500 rad/h). The fibres are single-mode and are all commercially available products: pure silica core fluorine doped cladding PSC/F_2 (type 1 and type 2), and match clad Ge-doped core. Results are shown in Fig. 10.

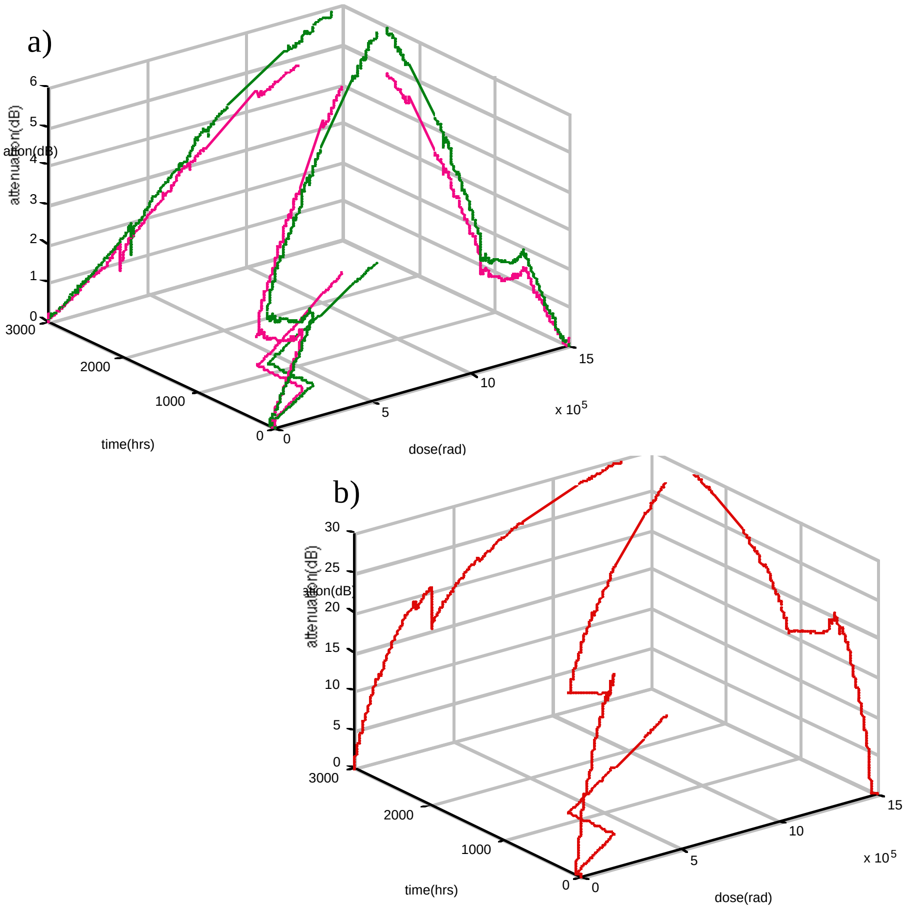


Fig. 10 - ^{60}Co γ radiation induced losses in single mode fibres. Length L=300m, spool diameter D=60mm, Wavelength λÅ 1540nm, optical power P~150µW, dose rate dD/dt Å 780 rad/h. a) rad hard PSC/F_2 type1 and type 2. b) standard telecom Ge-doped core fibre.

An increase in attenuation is clearly visible with rapid recovery when the source is turned off (t=578hr to t=1175hr). This recovery is not permanent for the PSC/F_2 fibres however, as transmission falls back to its pre-annealing value as soon as the irradiation is resumed. This result would indicate that some caution is necessary in deriving lifetime predictions from fibre annealing data.

The induced losses in the two PSC/F$_2$ fibres track remarkably well; the linear dose dependence of the attenuation, which is characteristic of a low dose rate irradiation, leads to a predicted loss of 0.15dB/year for a 10m long section of pure silica core fibre placed in the LHC detector area (assuming a machine operation cycle consisting of a 6 months irradiation period followed by a 6 months shut down, and neglecting recovery effects during shut down).

In comparison, the predicted values reported in [2] were 0.03-0.06dB/10m/year for PSC/F$_2$ fibre and 0.02dB/10m/year for Ge-doped fibre, based on high dose rate measurements (dD/dtÅ200krad/hr).

The results shown in Fig. 10, obtained with realistic dose rates, invalidate the earlier optimistic predictions for Ge-doped fibres, but confirm with much better precision the excellent properties of pure silica core fibres. The low accuracy of the kinetic model used in 1994 (especially in the Ge-doped case) probably lies in the difficulty of extracting the right coefficients out of the fit to the experimental points. Further tests are underway to clarify this issue, in particular a new series of measurements at high dose rate.

7.2 Modulators

Fully packaged devices are being irradiated. The test bench is the same as used for the optical fibres. The transfer function of 4 links based on two AFPM packages is measured at a hourly rate. Reverse current, dark current, laser power and temperature are also monitored. The modulator photocurrent characteristics (reverse current – dark current) and the link transfer functions of one of the four channels under test are shown in Fig. 11.

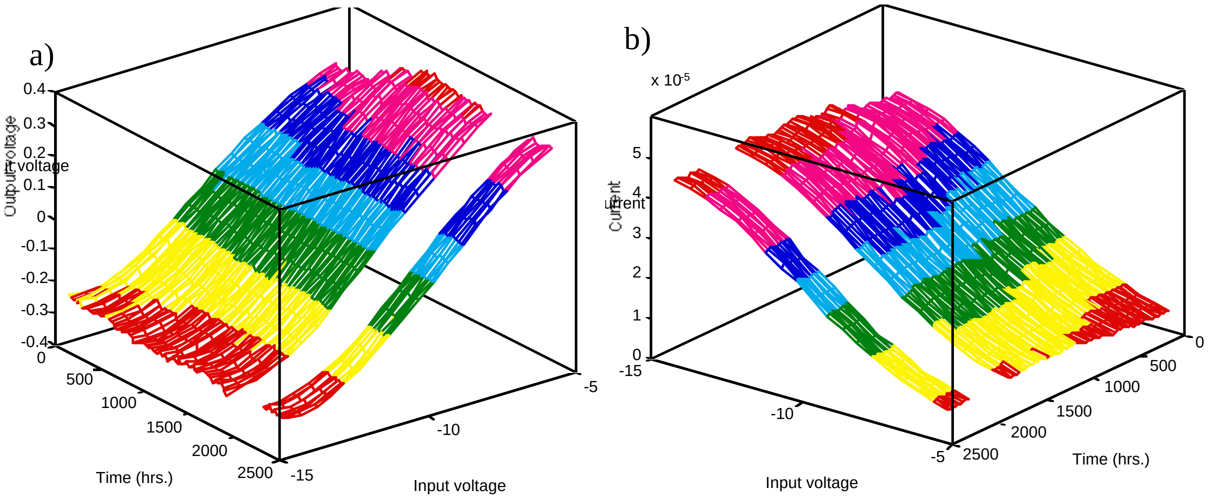
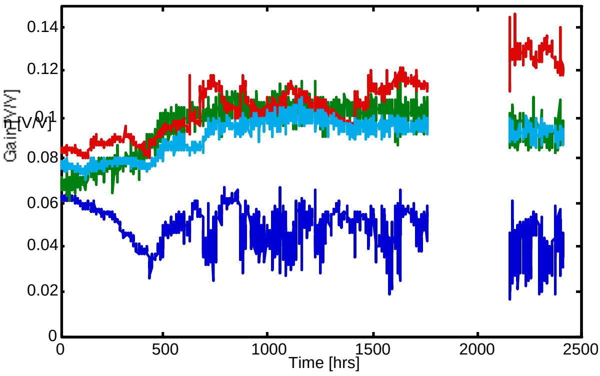


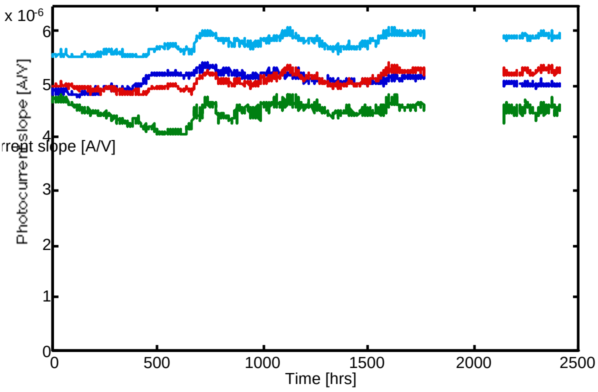
Fig. 11. Time dependence of a) AFPM transfer function, b) AFPM photocurrent.

The photocurrent is a good indicator of the intrinsic electro-absorption behaviour of the chip and of the incident optical power level. The link transfer function is of more difficult interpretation since it results from the folding of the reflectivity properties of the AFPM with the transceiver characteristics. The dark current (not shown) did not vary significantly for one of the two packages tested. It did increase for the other (reaching a few µA at Vbias for a 40µm diameter mesa), but the increase was not correlated to the dose profile [12].

From a link user point of view, one of the most interesting parameter is the dependence of link gain on time and dose as this ultimately determines the stability of the readout chain calibration. Fig. 12a shows the link gain at constant bias (Vbias Å -9V) obtained by calculating the derivative of the fitting polynomial around Vbias. As the number of experimental data points is limited in the linear zone, this operation introduces significant numerical noise into the plot.

The gain stability of 3 out of 4 channels lies in a ±20% range. The gain changes do not seem to be correlated to the total dose delivered. A possible cause for the fluctuations is the significant temperature variation over the observation time frame, which affects not only the modulator, but also the connectors and transceiver performance. The temperature was monitored inside the irradiation cell, but not in the control room (where the transceiver and one of the connector pair is positioned).





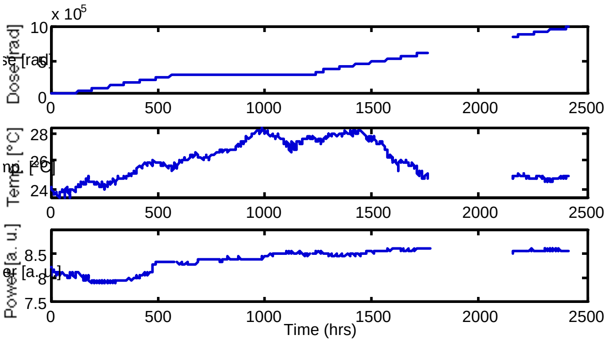


Fig. 12 - Time dependence of a) link gain and b) AFPM photocurrent slope under influence of ^{60}Co γ ray, temperature and optical power fluctuations. Butt coupled AFPM at Vbias Å –9V, FP laser (Popt Å 100µW), transceiver gain Gt Å 0.22V/µW

In an attempt to unfold the modulator characteristics from the rest of the system, the slope of the photocurrent function (see Fig. 11b) is plotted in Fig. 12b). Fluctuations are on the order of ±5% only, indicating that the AFPMs as individual elements may indeed be quite stable with time and dose. It is worth recalling that the reflected light detected in the transceiver has undergone a round trip through the system, while the light absorbed in the AFPM has travelled one way only; thus, all environmental perturbations along the link are likely to affect the modulated signal more strongly than the photocurrent. A detailed analysis of the data is currently under way and a report is in preparation [13].

High dose tests, to verify the results reported in [2,10], are scheduled in Nov. 1995. Neutron irradiation will follow early in 1996.

8. System issues

8.1 Connectors

To meet the practical needs of installation and servicing in LHC experiments, two optical link breakpoints are foreseen, at the front-end (on or close to the detector) and at the back-end (optical backplane on the readout board). As shown in sect. 7, the fibre segment in the vicinity of the detector should be of the rad-hard type, while ordinary telecom type fibre can probably be used elsewhere.

In the present design, the AFPM transmitters are pigtailed with single-mode fibre ribbons which are terminated with angle polished multiway MT ferrules [14]. Angle polished connectors assure low back reflections (return loss > 50dB) without the need for index matching gel. Eight such ferrules will be packed together into a high density matrix connector used at the link break points.

Mating losses and repeatability are still of some concern with the currently available MT connectors. Mating losses in excess of 1dB are still frequent and affect the power budget of the reflective link significantly. Moreover, the spread in mating loss from channel to channel will make individual adjustment of the receiving amplifier gain necessary. However, the performance of the connectors is steadily improving (better quality control of production). Despite the problems (and the additional cost), we are convinced connectorised breakpoints are required to meet realistic needs of link installation and servicing on detectors, and we plan to continue investigating the products available from industry.

8.2 Bi-directional links with AFPMs

Preliminary measurements, as reported in sect. 3.3, show that the AFPMs can be used as photodetectors with an acceptable crosstalk level between adjacent modulator and detector channels. Compared to the 1994 architecture, the system proposed in 1995 (see Fig. 1) integrates both analogue and digital channels (6+2 or 8+4) in the same multiway bi-directional fibre ribbon (8 or 12 way). At the front-end, a monolithic array of 8 or 12 AFPMs is partitioned into modulating and detecting devices. In the transceiver, directly modulated lasers are used to send the timing, trigger and control bits to the front-end. Such a full link demonstrator will be one of the main goals for 1996.

8.3 Reliability considerations

The access to the inner regions of the LHC detectors will be possible only during the shutdown period, and even then the complexity of the assembly will place considerable constraints on the servicing and replacement of faulty elements. The tracker might be envisaged as a "spaceship" to which access would be granted after launching only in case of major breakdowns. In this perspective, the reliability of the optical transmitters, even prior to irradiation, is particularly relevant since in general a number M of front-end chips, each containing N detector channels (N=128 typ.), are read out through each single link.

We may assume that a random loss of 0.2% per year of FE chip information, before taking into account radiation induced failures, would be tolerable. This corresponds to a median operational lifetime MTTF>10^7 hr, which is not an unrealistic target, since the currently achieved MTTF for commercial components representative of state-of-the-art VLSI is MTTF(chip) Å 10^9 hr (at T=25 °C). Thus the overall "availability" of the system can be expected to be determined by the transmitter reliability. Since the failure of one link results generally in the loss of the information from M front-end chips, the target requirement is MTTF(Tx)/M > 10^7 hr.

We first consider emitters: LEDs and laser diodes (LDs). The median lifetime of an emitter is determined by technology, packaging and operating conditions (mainly temperature). This is a rather complex subject and the considerations that follow are a rough oversimplification. The typical median lifetime of currently available emitters is shown in the table II.

Table II - Typical lifetime characteristics of emitters

emitter	λ (µm)	I_b (mA)	T_j (°C)	P_{fiber} (µW)	MTTF (hr)

GaAlAs LED	0.85	100	85	60	3x10^6
InGaAsP LED	1.3-1.5	100	85	12	5x10^6
laser diode (LD)	1.3	15	25 (case)	1,000	Å 10^6

In the case of LEDs, the optical power shown in the table is the one coupled through a microlens into a 50/125µm multi-mode fibre. Laser diodes, with a much higher conversion and fibre coupling efficiency, allow using single-mode fibres.

The operational lifetime of an emitter is usually determined for a 50% drop in light output power for a constant forward drive. The lifetime shows an exponential dependence on junction temperature (Arrhenius formula) and correspondingly on forward current. For example, by reducing the operating junction temperature of an GaAlAs LED from 85 °C to °5 C, the lifetime would be expected to increase by Å200x. Thus, it can be argued that by cooling the emitters in the same way as the semiconductor detectors during beam operation, and by using the lowest possible average drive current, a satisfactory lifetime will be achieved. However, it is likely that the detector will be operated around room temperature for long periods during shutdown, with a corresponding emitter lifetime reduction. Furthermore, emitters operated at low drive currents generally show higher sensitivity to radiation damage [15]. On the other hand, in the case of a graceful degradation, the gradual decrease in output power might be corrected for in the detector, particularly in the case of digital links.

Electro-optic modulators are structurally similar to photodiodes (and can indeed be used as such) so that we may expect them to have similar reliability features. The median lifetime of an InGaAs photodiode is estimated to be in excess of 10^9 hr at room temperature. Modulator-based transmitters (usually in the form of arrays) require however custom packaging that may eventually determine the overall operational lifetime.

Considerable advances have been recently announced in low-threshold MQW edge-emitting as well as vertical cavity surface emitting laser diodes (VCSEL). Several new devices and modules have reached the market place. The power coupled into a multi-mode fibre can reach Å 200µW at an operating current of Å 10mA. These emitters might eventually offer an interesting alternative to modulators, with some penalty in the higher electrical power required for the driver; however, their radiation resistance characteristics need to be measured. The structure of VCSELs is very similar to the one of modulators, and they are easily fabricated in linear arrays. Their wavelength is generally shorter than 1µm; the radiation hardness of optical fibres at these shorter wavelengths is expected to be lower than in the 1.3µm to 1.5µm region. Packaging requirements are similar to those for modulators. The linearity response and the median lifetime issues need to be investigated. We plan to put some effort in this activity depending on the resources available.

It should be pointed out that the reliability data for commercially available devices are typically based on measurements over several thousand units over several thousand hours. It is very unlikely that this process can be carried out on the semi-custom or custom devices that will be used in the LHC detectors. It may be necessary to rely on the well known properties of a specific technology and on the established packaging techniques.

Redundancy schemes can be envisaged, at the cost of increased complexity and power dissipation.

9. Proposed work programme and budget for 1996

We expect no major change in the HEP Institutes participation in the project, since members of ATLAS and CMS are already present in the collaboration. The sharing of responsibilities will be maintained as in the previous year. However, the larger number of trained scientists and the availability of link prototypes outside CERN will allow a more even sharing of the test and measurement work load.

The participation of the Interdisciplinary Research Centre for Semiconductor Materials (IRCS) in Oxford will be focused on modelling and growing AFPM structures, possibly also at a different (shorter) wavelength.

We have by now established very effective working relations with industrial partners for the three major technology areas required to develop the link:

- GMMT AFPM modulators; design, growth and packaging;
- ITALTEL Opto-hybrid transceivers; design, hybridisation, packaging
- EUROPTICS multiway ferrules and connectors, all issues related to fibre cabling

In the present advanced phase of the project, it would seem appropriate that these partners join formally the collaboration. EUROPTICS Ltd (UK) has already done so in 1995. Discussions are under way with ITALTEL (I) and GEC-Marconi Materials Technology Ltd (UK); certain intellectual property right issues have to be clarified.

It is also worth mentioning that in June 1995 we have submitted a proposal to the EC for a research network in the frame of the TMR (Training and Mobility of Researchers) programme [16]. The network would include several members of the RD23 collaboration (as well as teams which are not presently in the collaboration) and two industrial partners. The selection of proposals is expected to take place around end 1995.

9.1 Work programme

The RD23 developments are strongly driven by the timescale and requirements of the LHC experiments. To meet a number of milestones set for 1996 within both ATLAS and CMS, several decisions on technology options will have to be taken that could have significant impact on this project. The main questions concerning the fully integrated analogue optical link can be summarised as: (i) does it offer the required performance and reliability, and (ii) can it be produced by industry in volume quantity at affordable cost. We propose the following work programme with clearly identified goals to allow sound decisions to be taken in due time with a reasonable degree of confidence.

9.1.1 Performance assessment goals

Optical link demonstrator with 6 analogue (and/or digital) transmitters and 2 digital receivers

The modularity of the link is the one currently envisaged for the CMS tracker. This task requires the following main activities:

- characterisation of butt coupled AFPMs as photoreceivers;
- evaluation of modulator-receiver crosstalk;
- procurement and tests of low-power pulsed lasers and drivers (for the generation of digital signals at the back-end) and logic receiver amplifiers (for the front-end);
- integration of the transceiver with a prototype readout board (the CMS front-end driver (FED) developed at RAL).

We plan to use existing and soon to be delivered modulator arrays (transmitters) and transceiver prototypes. Results should be available by mid 1996.

9.1.2 Technology development goals

Assessment of the degree of control on the growth of the AFPM structures

Upgrade of the butt-coupled package from 4 channels to 8 channels

Feasibility demonstration of a compact hybrid transceiver

The following main activities are involved:

- characterisation of AFPM chips and evaluation of packaged devices;
- evaluation of passive waveguiding circuits for the transceiver;
- hybridisation of preamplifiers and PIN diodes.

Suitable preamplifiers (in die form) have already been identified. The work programme will make use of the industrial developments to be launched early in 1996. Results should be available in the last quarter of the year.

9.1.3 Cost assessment

Budgetary cost estimates are already available but need to be revised in view of changes in the target modularity of the system as well as cost trends of commercial components. We plan to provide the community with realistic budgetary cost estimates by Å mid 1996.

In addition, work has to be pursued (and intensified) on the following key issues:

- environmental effects on transmitters and transceivers;
- irradiation of transmitters and fibres;
- reliability study of transmitters and transceivers;
- non-linear preamplification to increase the effective dynamic range; this is based on a very recent CERN development [17].

9.2 Budget and resources

The budget requests for 1996 take into account the fact that the system company who provided matching funds for modulator developments has withdrawn its contribution. On the other hand, better conditions are likely to be obtained by negotiating directly with the industrial partners involved in technology developments. More significantly, we are entering a phase of developments focused on specific requirements of the LHC experiments, which will be called to contribute to the materials cost. Thus, we propose the following budget breakdown:

Financial contribution Activity	RD23/CERN (kSFR)	Exp. Collab. (kSFR)
Transmitter & transceiver developments	190	200
Electronics and F/O components	25	50
Irradiation tests	10	
Travel	15	
Total	240	250

A matter of serious concern is the scarcity of CERN resources presently allocated to the project, particularly in what concerns the specific fibreoptics and optoelectronics activities. It seems very difficult to find available staff with the required expertise. Several key tasks can only be carried out with the help of students and visitors, either from CERN programmes or from the experiments collaborations. A substantial increase in the level of support cannot be further delayed.

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W. Langhans, CERN (under way)

S. Oglesby, Birmingham (under way)

J. Troska, Imperial college (under way)

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