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Laser based optical links for the CMS tracker: options and choices

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Abstract

The CMS tracker optical readout links must fulfill demanding requirements such as radiation hardness, high reliability, small size, low power dissipation and low cost while maintaining a high analogue transmission quality during the experiment lifetime. The concept adopted for the CMS tracker is based on edge emitting InGaAsP semiconductor lasers coupled to pure silica core single mode fibre at the front-end, and InGaAs pin photodiodes coupled to Ge-doped single mode fibre at the back-end. The wavelength of operation is 1.31µm. Three patch panels based on multiway single mode connectors are foreseen for ease of testing, installation and maintenance. Baseline choices such as transmitter type, fibre type, operation wavelength and modularity are explained and justified.

1. Introduction

Among the variety of optical links being engineered for the CMS detector, the tracker readout links are particular and stand out in many respects: very large number of channels (> 50000 optical fibres), analogue data transmission, very stringent radiation hardness constraints at the front-end, excellent reliability requirements, etc...

The HEP community has been investigating candidate optical data transmission technologies for many years [1]. In particular, the RD23 collaboration [2] has thoroughly tested two alternatives promising to meet tracker requirements: direct modulation of light by an active transmitter situated at the link front-end (laser based link), and external modulation of light (generated at the link back-end) by a passive transmitter situated at the link front-end (modulator based link).

In mid-1996, the decision was taken to pursue only one of these two approaches in view of a future implementation in the CMS tracker: direct modulation of light by a laser transmitter [3].

The present note describes the laser based optical link currently being developed to fulfil the transmission system requirements (Fig. 1). Baseline choices such as transmitter type, fibre type, operation wavelength and modularity are explained and justified.

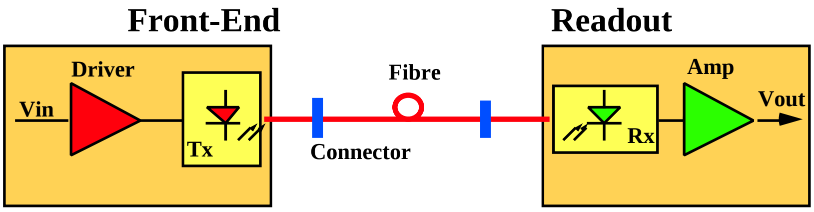

Fig. 1. Generic optical link based on a directly modulated laser transmitter (Tx) and a photodiode receiver (Rx).

2. Requirements

The CMS tracker readout chain has been described in detail in [4]. We summarise below the optical link requirements on:

2.1) performance,

2.2) environmental resistance,

2.3) physical layout,

2.4) reliability and

2.5) development timescales and cost.

A more detailed specification can be found in the draft document [5].

2.1 Performance

Each optical link transfers pulse amplitude modulated signals in sequences of 256 detector channels, time multiplexed at a rate of 40MS/s. The sequence frequency is Poisson distributed around a 100kHz average value. The required dynamic range is 7-8 bits with a tolerated linearity deviation of ~2 percents.

2.2 Environment

The front-end part of the link (transmitter, fibre, connectors) must be resistant to total doses and fluences in excess of ~10Mrad and ~10^{14} n-equivalent/cm^2. It will be operated in a temperature controlled and dry atmosphere. The power dissipation of the transmitter should be kept as small as possible (typ. ~50 mW/optical channel) and low mass non-magnetic material should be used wherever possible.

On the back-end side of the link, conventional uncontrolled operating conditions are assumed (0-70°C), with no radiation resistance constraints whatsoever.

2.3 Physical layout

The optical link length is typically 100m, of which the first ~10m run inside the detector and must thus be radiation hard. Based on a 256:1 multiplexing ratio, about 50000 optical links will be required to read out the CMS tracker. Space is at premium all over the detector- and readout area. Compact packages must be used for transmitters and receivers, fibre must be bundled into ribbons, and multiway connectors must be arrayed into dense patch panels.

The need for compact assemblies must however be traded off against the diverse and physically distributed nature of the detector elements. Ultra-compact transmitter packages serving a large number of ways (up to 12 fibres can be ribbonised) are unattractive as they would in most cases require to electrically fan in analogue signals from distant detector elements, eventually degrading transmission quality and potentially causing noise pickup problems.

2.4 Reliability

Access to the detector front-end once high luminosity operation will have begun will be extremely difficult, if not impossible. High reliability electro-optical components will have to be installed if the target failure rate of less than 1%/calendar year for the whole readout chain is to be met.

2.5 Development timescales and cost.

Working backwards from the CMS operation starting date of 2005, large scale production of optical links should commence in 1999, extending over a 2-3 years period. Specifications should thus be frozen no later than end of 1998 after completion of a robust qualification and prototyping phase.

Target cost is about 150SF/optical link, still a very aggressive figure compared to current market prices and forecasts.

3. Technological options

Optoelectronics is still a relatively young technology. Quite a broad variety of components are commercially available, but only a few standards have emerged over the years, most of them being linked to telecommunication applications.

The optical system designer is thus faced with choices which cannot always be met by clear-cut decisions. We review in this section the tradeoffs involved in choices of:

3.1) laser type,

3.2) operation wavelength and

3.3) fibre type.

A thorough discussion of available technologies is beyond the scope of this work, but can be found for instance in [6, 7]. Only a few relevant key points are highlighted below and only certain options are considered (Fig. 2). Experienced readers are invited to skip this section and proceed to section 5, where the choices made for the CMS-tracker link are presented.

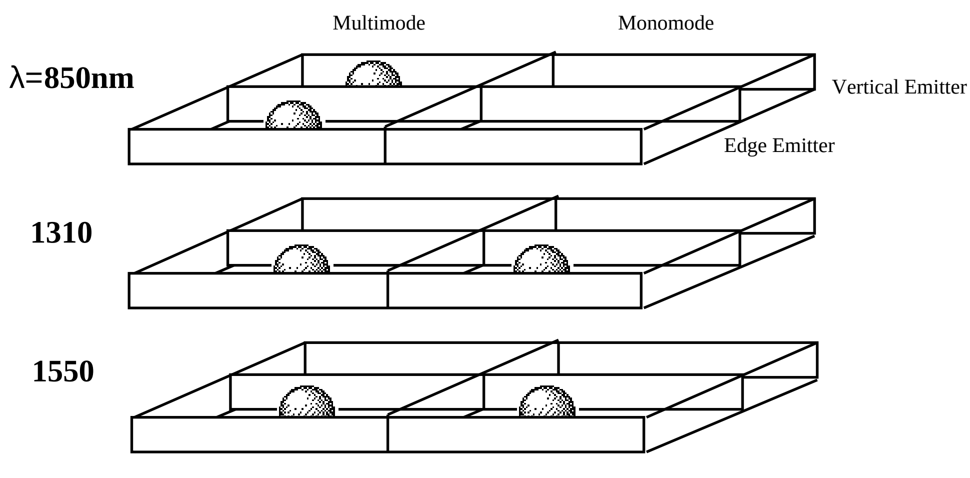

Fig. 2. Considered options (bullets) in the technology parameter space.

3.1 Laser type

Semi-conductor lasers have traditionally been available as Fabry-Perot *edge emitting devices*, where the light is amplified and emitted *in the plane* of the wafer and the cavity mirrors are formed by the cleaved crystal facets. Recently, *Vertical Cavity Surface Emitting Lasers* (VCSELs) have become commercially available, where the light is generated and amplified *perpendicularly* to the plane of the wafer. In this case, the cavity mirrors are distributed.

Thanks to their vertical structure, *VCSELs* can be produced as compact bi-dimensional arrays of on wafer testable devices, making efficient use of the expensive epitaxy area. The pixel-like active area (typically <10µm diameter for monomode devices) ensures circular low divergence light emission and, for small diameter devices, low threshold current as well as potentially excellent radiation resistance [8]. However, the small volume high Q cavity stores a very high energy density and heat management remains a difficulty, especially for arrays. Most VCSELs are strongly non linear in characteristic, emit a beam with non-defined polarisation state, operate only at infra-red wavelengths below 1µm, and are targeted at low cost high volume digital applications. Up to this date, very little data has been made available on reliability [9] and there exists no field record of VCSEL failures. Overall, the technology is still rapidly evolving.

Edge emitting lasers, when compared to VCSELs, can be considered mature. Their long cavity (typ. 300µm) uses up more wafer real estate, but guarantees good thermal management, highly linear characteristics and high output powers. Edge emitters are tested at the cleaved bar level (linear arrays) and emit an elliptical beam with relatively high divergence, which makes the fibre coupling process difficult and costly. Devices operating at numerous infra-red and visible wavelengths have been successfully installed for both digital and analogue applications. In the last 15 years, impressive technological progress has been achieved and several manufacturers now quote laser lifetimes on the order of 10^6 hours, based on extensive field studies. The radiation resistance of edge emitting lasers has been discussed in [8].

3.2 Operation wavelength

Different material systems can be engineered to produce devices emitting light at various wavelengths. In the near infrared, two systems dominate: GaAs-AlGaAs for λ 0.7−0.9µm and InP-InGaAsP for λ 1.2−1.7µm. Correspondingly, on the light detection side, Si pin diodes are conventionally used in the 0.7-0.9µm window while InGaAs pin diodes operate in the 1.2-1.7µm window.

Two wavelength standards have emerged in the telecom long distance applications: λ=1.31µm for low dispersion and 1.55µm for low attenuation transmission. Most long wavelength semi-conductor lasers are specified at one of these two wavelengths. Edge emitting lasers operating at 1.31 µm currently feature better performance and lower cost per given output power than 1.55µm lasers. As mentioned in 3.1, no commercial VCSELs operate in the long wavelength range.

In the 0.7-0.9µm window, no “universal” standard exists. The market is driven by CD edge emitting lasers with no tight requirements on operating wavelength. Due to the high volume of devices produced annually, prices are low. This may however change in the future as CD lasers will make use of other materials emitting in the visible.

When irradiated, optical fibres develop absorption peaks called colour centres. For the infra-red wavelengths of interest, the dominant colour centre peaks at 680nm [11]. The shorter the wavelength of operation, the more pronounced will be the attenuation caused by the tail of this visible colour centre.

From a safety point of view, laser products are rated differently depending on their operation wavelength. Class 1 lasers (eye safe) can emit no more than 0.22mW at λ=700nm, but as much as 10 mW at λ=1.4µm [10]. Long wavelength systems are thus inherently safer than short wavelength ones. If a class 1 system cannot be designed, a class 3A product (safe for viewing for 100s with unaided eye) must include interlocked controls.

3.3 Fibre type

The core diameter of an optical fibre, its refractive index profile as well as the operation wavelength determine whether one single- or multiple optical modes can propagate in the glass. Typically, single mode systems feature a core diameter smaller than 10µm and an abrupt refractive index step between core and cladding; multimode systems feature a core diameter between 50 and 200 µm and sometimes an engineered refractive index profile (graded index) which allows to minimise the modal dispersion.

It is once again the telecommunication operators who have set standards for single mode fibre: 9µm core, 125µm cladding, 1.31 or 1.55 µm wavelength of operation. Typical characteristics of single mode telecom fibre at 1.31 µm are: 0.3dB/km attenuation and 500Gb/s*km bandwidth. About $25*10^6$ km of single mode fibre are produced annually, making telecom fibre a cheap mass product.

In comparison to telecom fibre, the multimode fibre market is segmented into many standards and applications. Two of the main standards are 50µm or 62.5µm core, 125µm cladding diameters. Typical characteristics at

0.85µm (1.31µm) wavelength are: 2.5dB/km (0.7dB/km) attenuation and 300Mb/s*km (1Gb/s*km) bandwidth for graded index fibre. Multimode fibre is currently about 3 to 5 times more expensive than single mode. This should however be balanced with the cheaper cost of the light coupling elements (connectors and pigtails) for multimode systems due to the looser alignment tolerances. A single mode multiway connector typically costs two to three times as much as a multimode one. Cost comparisons are however difficult to project into the future as changes in volumes may completely modify the current price ratios.

Radiation resistant fibre usually features an undoped pure silica core, and is thus of the step index type. Whereas this does not affect the single mode system design (step index fibre being used throughout), it makes the multimode system heterogeneous by connecting in series a short length of step index radiation resistant fibre with a graded index conventional fibre. Step index multimode fibre has a bandwidth of only 30Mb/s*km, essentially limited by modal dispersion.

Finally, an important parameter for a multimode analogue transmission system is the amount of modal noise, where temporal fluctuations of the modal energy distribution in the fibre may be transformed into intensity noise at every connector interface. Short multimode links with numerous breakpoints are prone to modal noise.

4. Commercial developments

In order to keep the development and purchasing costs of an optical fibre system as low as possible, a careful look at available commercial products and trends is instructive.

The great majority of optical transmission systems installed in the world today are digital. Historically, long distance high capacity point to point links have been the first ones to be deployed by telecom operators at long wavelengths (1.31 or 1.55µm) and with single mode fibre. Since then, the telecom network has grown to the point where optical fibre is being intensively installed in metropolitan areas, even to individual buildings or homes, still complying with the same standards. Components developed for telecom applications are long wavelength, single mode, long lifetime (typ. 15 years) and highly reliable devices. However, unless every home is outfitted with an electro-optic interface, telecom components will tend to remain expensive as the current production volumes do not justify a heavy investment in mass production tools and processes.

Datacom short distance fibre optic links serving computers and peripherals are now becoming quite common. They are usually based on short wavelength, multimode technology and target medium to short lifetime (typ. 5 years) easy replacement products. Unless these links can find applications in consumer electronic devices, their cost will also remain quite high.

The only analogue fibre optic systems being laid out in significant mileage today are broadcasting networks for cable TV and high bandwidth cellular antennas. They are based on long wavelength, single mode components optimised for linearity and high power at the Tx side and will remain expensive for any foreseeable future.

5. Baseline choices for the CMS tracker optical links

Comparing the CMS tracker requirements presented in section 2 with the commercial developments discussed in section 4, it is clear that no direct and perfect match between the two is possible. Whereas the short length of the link and its low cost target might be best met by datacom type components, the environmental resistance-, the reliability- and lifetime-specifications as well as the requirements linked to an analogue mode of operation are more typical of telecom applications. In any case, it should be pointed out that the front-end constraints of reduced footprint, low mass, non-magnetic and radiation resistant packages are particular to our application and will necessarily impose a certain amount of package customisation.

In order to be able to carry out the needed developments and tests in good conditions and with clear specifications in view, and given the tight time schedule to design freeze, an early choice of the component types used for the CMS tracker optical readout link is mandatory. Figure 3 shows the baseline concept: transmitters are edge emitting lasers, fibre type is single mode, wavelength of operation is 1.31µm. At the front end, a modularity of 4 transmitters serving 1024 detector strips is proposed. Optical fibre ribbons originating from the transmitter hybrids are fanned-in after the second patch panel to 64-fibre cables running outside the tracker volume. Each cable connects 16 transmitter modules to one FED readout board.

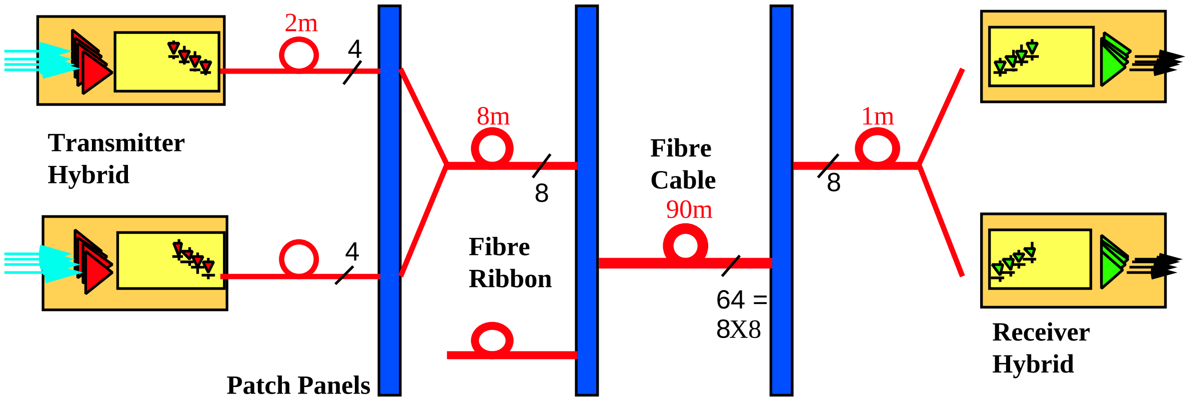

Fig. 3. Analogue optical link layout

The decision to retain edge emitting lasers was essentially driven by their good analogue performance (linearity), proven reliability, existing field record and the availability of well established laser-fibre coupling techniques compatible with our environmental requirements. Functionality and radiation resistance tests of commercially available edge emitting lasers have been successful, opening up the possibility of hybridising commercial chips into a customised package and thus reducing the development effort and risk. The VCSEL alternative clearly would have featured some attractive characteristics and had a potential for further development. However, choosing to use VCSELs at this relatively unmature stage was perceived as too risky given our front-end requirements and development timescales. Moreover, it would most certainly have led to custom developments of both chip and package.

The chosen fibre is of single mode type. This avoids the uncertainties linked to modal noise in multimode analogue systems and makes the realisation of a homogeneous fibre link possible, with step index fibre used throughout (pure silica core inside the detector, germanium doped outside). Based on our current cost model, both single mode or multimode links (10m rad hard step index, 90m standard telecom, 3 patch panels) cost approximately the same, including connectors. However, whereas coupling light *out of* a fibre into a photodetector is as easy in a multimode as in a single mode system, coupling light *into* a single mode fibre can be much more difficult than into a multimode fibre and may induce a transmitter cost penalty. Given the modest optical power levels required and assuming an active assembly technology, monomode laser transmitters have however been estimated to be only about 10% more expensive than multimode ones. A clear cost advantage in favour of a multimode transmitter would only be reached when using passive alignment schemes which however are not recommenced when assembling multiway modules and are not common practice in industry today. Edge emitting lasers pigtailed with single mode fibre are and will remain the telecom standard for many years. Moreover, edge emitting lasers with integrated mode size converters now start becoming available, thus easing the coupling process to single mode fibre and reducing packaging costs [12].

A long wavelength of operation (1.31µm) allows: a) to use standard and cheap single mode telecom fibre, b) to minimise the effect of radiation induced fibre darkening, and c) to operate an eye safe ribbon-based system at power levels compatible with our application. The choice of λ=1.31µm instead of 1.55µm was motivated by the lower cost and better performance of laser transmitters at this wavelength.

The coupling technology between the single mode fibres and both the transmitter and receiver rely on a planar Si-subassembly serving as platform for alignment of die and fibre. This technology is now finding widespread use in industry and commercial one-way packages have been successfully tested for functionality and radiation hardness. It is likely that many industrial sources for one-way subassemblies will be available in the short term.

Four-way small footprint low mass packages based on packed one-way Si-subassemblies are currently being custom developed for CMS by European industry. A base modularity of 4 optical channels per package represents a good trade-off between the distributed nature of the tracker detector (in particular barrel MSGC) and the requirements for compactness and ease of installation of the readout system. Eight way packages could also be envisaged for the receiver side of the link, to be mounted on the FED readout board. Additional information is available in [13].

6. Development and prototyping timescales

Assuming a design freeze at the end of 1998, the bulk of the development work will have to be concluded by mid 98 to allow for final prototype testing and write-up of the specifications. The currently ongoing industrial programme calls for delivery of the first 4-way packages in early 98. Radiation hardness and reliability tests may however take much longer than a few months to produce useful results. The current strategy to overcome this timescale problem is to test one-way components thoroughly in 1996 and 1997 already, and only to confirm these results with the 4-way custom components delivered in 1998. This is scientifically sound as both the chips and coupling technology will be the same for 1-way and 4-way components.

In parallel to internal qualification tests, prototype analogue links comprising laser driver, transmitter, receiver, transimpedance amplifier, fibre and optical connectors will be distributed to the CMS community for evaluation: 1-way links will be ready by mid 97, 4-way links by mid 98. It is hoped that feedback from external users will allow to define a widely accepted analogue optical link standard by end of 1998.

7. Conclusions

The optical link concept retained for the CMS tracker readout system is based on edge emitting semi-conductor lasers as transmitters, InGaAs Pin photodiodes as receivers and single mode optical fibres and connectors as transmission media. The active components are mounted on planar Si subassemblies and packaged into mini-DIL type housings with a fibre ribbon or bundle pigtail. The base modularity is 4 ways per package.

The proposed system is very much in line with the current and emerging telecom standards. It will thus benefit from technology improvements, multiple sources availability and cost reductions expected in the coming years. It sets a platform which could be common to all analogue and high speed digital links throughout CMS. It allows to proceed via the safest route towards implementation of a functioning radiation-hard and reliable optical link in a relatively short development time. As with any high technology project however, an early design freeze increases the risk that the chosen components and standards will be obsolete by the time the experiment will be running. The inertia of the telecom operators and the wide installation base of their optoelectronic equipment however make us confident that following their standards represents the most stable and least risky way forward, both in terms of technology and cost.

References

[1] Optoelectronics sessions, proceedings of first Workshop on Electronics for LHC Experiments, Lisbon, Sept. 11-15, pp. 155-84, CERN/LHCC/95-56 (1995), proceedings of the second Workshop on Electronics for LHC Experiments, Balatonfuered, Sept 23-27, pp. 363-400, CERN/LHCC/96-39 (1996).

[2] RD 23 status reports, CERN/DRDC 93-35 (1993), CERN/DRDC 94-38 (1994), CERN/DRDC 95-61 (1995).

[3] G. Hall, G. Stefanini, F. Vasey, “Fibre optic link technology for the CMS tracker”, CMS note 1996/012.

[4] G. Hall, “Analogue optical data transfer for the CMS tracker”, NIM A 386, pp. 138-42, (1997).

[5] F. Vasey, “CMS tracker optical readout link specification, draft version 0.5.

[6] C. Davis, “Lasers and Electro-Optics”, Cambridge University Press, 1996.

[7] J. Gowar, “Optical communication systems”, Prentice Hall, 1993.

[8] K. Gill, R. Grabit, G. Stefanini, F. Vasey, "Radiation Damage Studies of Semiconductor Lasers for the CMS Tracker Optical Data Links", proceedings of the second workshop on electronics for LHC experiments, Balatonfuered, Sept 23-27, 1996.

[9] K.L. Lear et al., “Life testing oxide confined VCSELs: too good to last?”, SPIE 2683-17, 1996.

[10] International standard IEC 825-1, first edition, 1993-11.

[11] Y. Morita et al., “Dose rate effect on radiation induced attenuation of pure silica core optical fibres”, IEEE Trans. on Nucl. Sci., Vol. 36, No. 1, pp584-90, 1989.

[12] T. Hashimoto et al., “hybrid integration of spot-size converted laser diode on planar lightwave circuit platform by passive alignment technique”, IEEE Photonics Technol. Lett., Vol. 8, No. 11, pp. 1504-6, 1996.

[13] http://www.cern.ch/CERN/Divisions/ECP/CME/OpticalLinks/