

Development of rad-hard laser-based optical links for CMS front-ends

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ABSTRACT

We present the concepts underlying the development of a rad-hard optical link based on edge-emitting laser transmitters, single-mode optical fibre ribbons, multi-way MT connectors and pin-photodiode receivers operating at a wavelength of 1310nm. One-way transmitter- and receiver-building blocks, assembled into 4-way packages using silicon-submount technology, allow for high flexibility and modularity in the system design. This is illustrated by reviewing both the analogue-readout and digital-control optical systems of the CMS tracker, which are based on identical optoelectronic components but achieve different functionality. Ongoing developments and timescales to production are discussed.

1. INTRODUCTION

The CMS experiment is planning to use large quantities of optical links for analogue and digital data readout as well as digital control and timing signal distribution. In particular, front-end links connecting pixel, tracker and calorimeter detectors to the front-end driver and controller modules will need to be radiation resistant, and thus deserve special developments and qualification procedures.

A radiation-hard optical link featuring characteristics suitable for analogue as well as digital applications is being developed for the CMS tracker. The flexibility of the assembly procedure used to package the optoelectronic components, as well as the 4, 8 or 12-way modularity of the fibre ribbons, cables and

connectors allow to adapt the optical link configuration to a great variety of system architectures.

In section 2, the optical link is presented and described, while two system applications (one analogue and one digital) are reviewed in section 3. The evaluation of component radiation hardness as well as analogue and digital link performance are briefly reviewed in section 4, but more details can be found in the accompanying papers [1,2,3]. The development status and schedule to production is presented in sections 5 and 6.

2. DESCRIPTION

The optical link under development for the CMS experiment is schematically shown in Fig. 1. It is a 4-way unidirectional system based on edge-emitting laser transmitters (Tx) coupled to single mode optical fibre, multi-way MT connectors and pin-photodiode receivers (Rx). The wavelength of operation is 1310nm. The driving and receiving electronics is designed according to the system application: analogue for the readout-, and digital for the control-system of the CMS tracker for instance. The total link length is approximately 100m, of which about 10m is within the detector.

a) Opto-electronic components description

The opto-electronic transmitter and receiver components are assembled by aligning on a Si-submount the laser- or pin-diode die to a single mode fibre (Fig. 2). This technology, now being adopted by all major telecom component manufacturers [4], is well adapted to the fabrication of single element devices, hybrid assemblies or arrays. Good optical coupling between die and fibre is achieved with micro-machined V-grooves self aligned to die-attach metal pads and

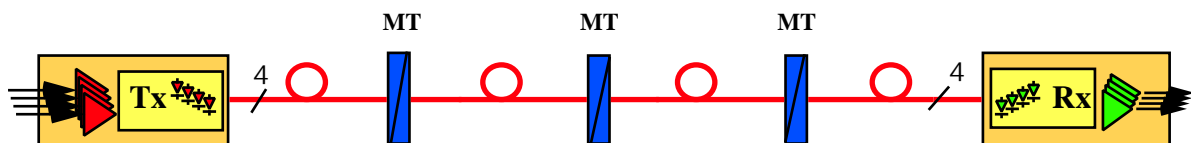


Fig. 1. Generic optical link block diagram.

registration marks. The resulting assembly is a mechanically rugged, low mass, small footprint (typically 2.5mm x 1.9mm) module, which can easily be handled and tested before packaging.

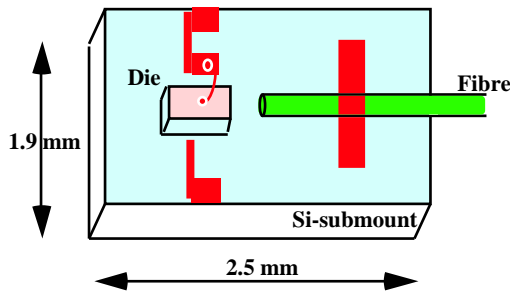


Fig. 2. Schematic diagram of laser- or pin-diode assembly on Si-submount.

The laser chips are commercially available Multi-Quantum-Well (MQW) InGaAsP edge-emitting devices selected for their good linearity, low threshold current (~10mA) and proven reliability. Photodiodes are InGaAs epitaxially grown devices of small active volume (typ. 75µm diameter x 3µm thickness). Both laser and pin diodes have intrinsic bandwidths in excess of 1GHz and can be used alternatively in analogue or digital systems.

Assemblies of up to four laser- or pin-diodes (or a mixture of both) are housed in a single (custom developed) non-magnetic package approximately 15mm x 10mm x 4mm in size (see section 5).

b) Passive optical components description

The passive optical components (fibres and connectors) are single mode devices operating at a wavelength of 1310nm, in line with telecom standards. This choice limits the optical modal noise contribution to the overall link noise budget, and allows to use step index radiation-resistant undoped silica-core fibre inside the detector without compromising the system bandwidth. It thus guarantees a high degree of performance for both analogue and very high speed digital applications.

Individual fibres are grouped into multi-fibre ribbons (4- and 8-way) and multi-ribbon cables (typ. 8x8-way) based on currently available commercial products. Three connectorised breakpoints (two inside the detector and one on the backplane of the readout electronics) allow for easy testing, installation and maintenance of the system. Connectors based on angle polished MT 4- and 8-way ferrules [5] are used throughout, achieving the highest patch panel density currently possible with commercial components.

3. APPLICATIONS

The optical link described in section 2 has a potential dynamic range in excess of 50dB (peak signal to rms noise voltage ratio) in a 100MHz bandwidth for analogue applications and a potential bandwidth in excess of 1Gb/s for digital applications. Its modularity has been optimised to 4 channels per package but can be easily reduced by partly populating the assemblies, or increased by grouping packages onto common modules with 8 or 12 way ribbon pigtailed and connectors.

We describe below two particular applications currently under study for the CMS tracker, but the concept is clearly flexible enough to accommodate varied system requirements. In particular, the optical link high radiation resistance will make it compliant with almost any sub-detector specification.

a) CMS-Tracker analogue readout

The CMS-tracker readout application is extremely demanding in terms of performance, radiation resistance and volume/cost targets [6]. As such, it received most attention in the past years [7,8], and is now driving the optical link development effort reviewed in the present paper.

The projected optical system layout is shown in Fig. 3.a (preliminary). It is a unidirectional link with analogue, time multiplexed information flowing from the front-end (left) to the readout area (right) at a rate of 40MS/s. About 50000 optical links are needed to readout the CMS tracker, each link serving 256 detector channels. To increase cable and patch panel density, 4 way ribbons are merged to 8 ways at the first patch panel situated at the edge of the tracker mechanical support structures; 8-way ribbons are then packed into 8-ribbon cables (64 way) at the second patch panel situated in the EM-Calorimeter crack. The 64 fibre cable fans out at the third patch panel situated at the backplane of the FED readout board. To accommodate the different tracker sub-detector modularities and geometries, it is planned to allow for some variants of this baseline architecture, in particular by installing some partly populated transmitter packages in low granularity detector regions.

All electronics and optics between the front-end and the second patch-panel (inclusive) are required to be radiation hard [9]. A detailed specification of the CMS tracker optical readout system is available [10].

b) CMS-Tracker digital control

The projected layout of the optical part of the CMS-tracker control system is illustrated in Fig. 3.b. It is a bi-directional link with control data, clock and T1 signals sent from the back- to the front-end (left), as well as status data and clock signals returned from the front- to the back-end (right)[11]. The bit rate is 40Mb/s. For redundancy reasons, the number of lines is

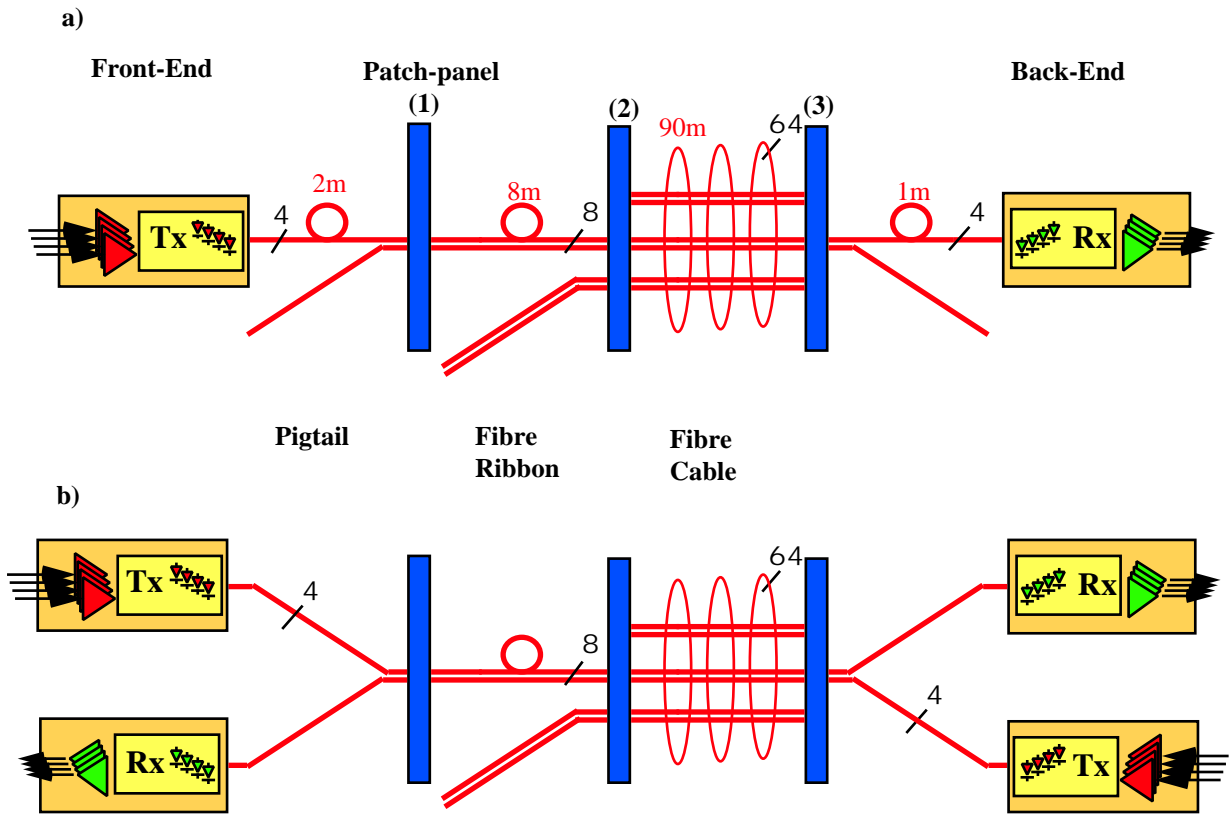


Fig. 3. Two system applications for the CMS-tracker (preliminary, only optical system is shown): a) analogue readout, b) digital control.

doubled, resulting in a modularity of 4 transmitters or 4 receivers per package, as in the case of the analogue readout system. The similarity of the two layouts is evident from Fig. 3. The number of links needed for the control system will be about two orders of magnitude smaller than for the readout, but the technologies and components used will be identical. All electronics and optics between the front-end and the second patch-panel (inclusive) are required to be radiation hard. Thus, in addition to the components already qualified for the readout system, pin-diodes, transimpedance amplifiers and digital post-amps must be resistant to the inner tracker environment.

4. EVALUATION

Most components foreseen to be used in the optical link have been evaluated for performance and radiation hardness. Laser transmitters have been early recognised as the most critical element of the optical transmission chain, and as such have been extensively studied [8,12-17]. Commercial devices from seven different manufacturers have been tested in die and/or packaged form, with qualitatively identical results; provided that the link operating point can be adjusted over the

experiment lifetime to track radiation damage, edge-emitting lasers packaged using Si-submount techniques are good candidate transmitters for operation in the CMS tracker environment. Detailed test results of lasers and pin diodes irradiated up to fluences of 10^{15} n/cm² (6MeV neutrons), and 4×10^{14} p/cm² (24GeV protons) as well as doses of 100kGy (⁶⁰Co-gammas) are reported in the accompanying paper [1]. Test results for fibers and connectors have confirmed that very little degradation of their optical and mechanical properties will be observed under LHC operating conditions [13, 14, 15].

The unirradiated component reliability quoted by manufacturers is based on internal qualification tests and external field-data. Typical mean time to failure values are well in excess of 10^6 hours at room temperature and for low optical power levels [18, 19]. Small scale lifetime tests of irradiated devices are in preparation.

Complete analogue and digital data link prototypes have been successfully engineered [16, 17], using the opto-electronic components described above and discrete off-the-shelf electronics. Test results confirm that a dynamic range of 50dB, a linearity deviation of less than 2% and a bit error rate of less than 10^{-12} are achievable with some safety margin [2]. As the receiver part of the analogue link prototypes can be directly plugged into

the FED readout boards, evaluation of performance in a realistic environment is possible. Integration of an optical link in an emulated CMS-tracker readout chain is reported in [3]. The system operation is quantitatively evaluated using powerful software routines and algorithms.

5. DEVELOPMENT

The optical link development effort aims at qualifying commercially available products and technologies wherever possible, and developing only what is not currently available or absolutely specific to the LHC application: rad-hard electronics, low mass, small footprint, non-magnetic optoelectronic packages and compact optical patch-panels. The fast and low cost access to sophisticated components is the obvious advantage of such a minimal development strategy, but the risk to bear in mind is the lack of influence on the manufacturer and the absence of any guarantee on the stability of the radiation hardness properties of the manufacturing process. The good behaviour of all active and passive commercial components tested to this date under irradiation (from different lots and different manufacturers) indicates that this risk is minimal. At production time however, every batch delivery of commercial components will have to be individually qualified before being installed in the tracker front-end.

Besides components qualification and system evaluation, the CMS internal development effort for the tracker optical links is mainly devoted to electronics. This includes discrete analogue and digital circuits for rad-soft prototypes [2,17] as well as design, integration and test of analogue laser driver [20] and digital receiver ASICs to be eventually transferred into rad-hard processes.

The external developments are centred around optoelectronic components. They are carried out with the help of leading edge industrial companies involved in component manufacture, packaging and connectorisation. Our request for compact multiway packages and patch-panels is one to two years ahead of emerging industrial products and standards. As such, it needs to be addressed in parallel to the commercial developments to avoid engineering full custom devices incompatible with future products. In this perspective, staying aligned with telecom standards (single mode system, 1310nm operation wavelength) guarantees the long term applicability of the development effort.

Parallel competitive development and evaluation programs are running with two opto-electronic device manufacturers and two optical connector manufacturers. The goal is to deliver 4-way transmitter or receiver modules in low mass, small footprint, non-magnetic packages, and dense 32 to 64 way optical connectors. The laser- and pin-photodiode chips as well as the multi-way connector ferrules are commercial components being qualified for operation at LHC via ongoing intensive test procedures. Only the compact packages

and connector shells are custom developed with industry. Second sourcing at the component level is possible as chips and ferrules from various manufacturers can be assembled onto identical Si-submounts and connectors. For example, laser chips from different origins have been supplied by one industrial partner, and have successfully passed irradiation tests.

Obsolescence is a serious issue to be considered in the light of a long term project like LHC. Telecom operators (who are the main users of the components under evaluation) typically require from manufacturers that products remain on the market more than 5 years after their introduction. A significant advantage is thus gained by complying with telecom standards, increasing the confidence in device availability until the construction phase of LHC has started. Written guarantees have already been requested from some manufacturers.

6. TIMESCALES

The optical link development schedule is constrained by the CMS-project timescales and the long foreseen cycle time for production, testing and installation into the detector.

Production is scheduled to start in 2000 with a pre-production phase in 1999. It should extend over a 3 years period with a delivery of about 18000 links per year. Both funding and testing efforts will have to match this pace. Specifications will need to be frozen by the end of 1998, which leaves very little time for any remaining development.

This tight schedule lead in the past to early technological choices and a focused development effort with as little customisation as possible [8,21]. As a result, the first custom developed 4-way packages will be available at the end of 1997. By then, validation tests (performance and radiation resistance) will have been carried out on one-way packages assembled using the same die and Si-submount technology. Only a limited set of stringent tests will be run on 4-way modules.

Discrete rad-soft electronic circuits for drivers and receivers have been developed and built to evaluate analogue and digital link performance, and to help elaborate specifications based on experimental data. As ASICs become available, they will gradually replace the discrete circuits in the chain. Prototype analogue one-way optical links have now been made available to the CMS community in the form of a modular evaluation platform including driving and receiving electronics. Digital links compatible with this platform will follow by early 98. The first 4-way links will then be assembled with the custom developed 4-channel driver ASIC. They will be available by mid 98. By distributing optical link prototypes early enough for beam tests and independent evaluations to take place, it is expected to receive valuable feedback from users before the specifications are frozen.

7. CONCLUSIONS

The presented optical link concept is based on MQW edge-emitting InGaAsP semiconductor lasers as transmitters, InGaAs Pin photodiodes as receivers and single mode optical fibres and connectors as transmission media. The active components are assembled on planar Si-submounts and hybridised with a base modularity of 4 ways per package. Evaluation of both radiation resistance and operational performance have been successfully carried out on 1-way components and systems. Integration into an emulated analogue readout chain has been reported for the first time.

The proposed optical system is now being distributed in prototype form within the CMS community. It sets a platform which could be common to many analogue and high speed digital links. It allows to safely proceed towards implementation of a functioning radiation-hard and reliable optical link in a relatively short development time.

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