SpaceFibre
Fibre-optic Link

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The SpaceFibre Development

- ESA study “Optical Links for the SpaceWire Intra-Satellite Network Standard”, i.e. “SpaceFibre” in 2004 - 2006
- SpaceFibre aims to be the optical fibre extension of the SpaceWire standard
- The SpaceFibre development team:
  - Patria (Finland): Prime, Interface electronics, Environmental testing
  - VTT (Finland): Optoelectronics transceiver module
  - INO (Canada): Optical fibre
  - Fibrepulse (Ireland): Fibre optic connectors and cable assemblies
  - W. L. Gore (Germany): Optical fibre cabling
  - University of Dundee (UK) in a parallel ESA activity: SpaceFibre CODEC, SpaceWire – SpaceFibre Router

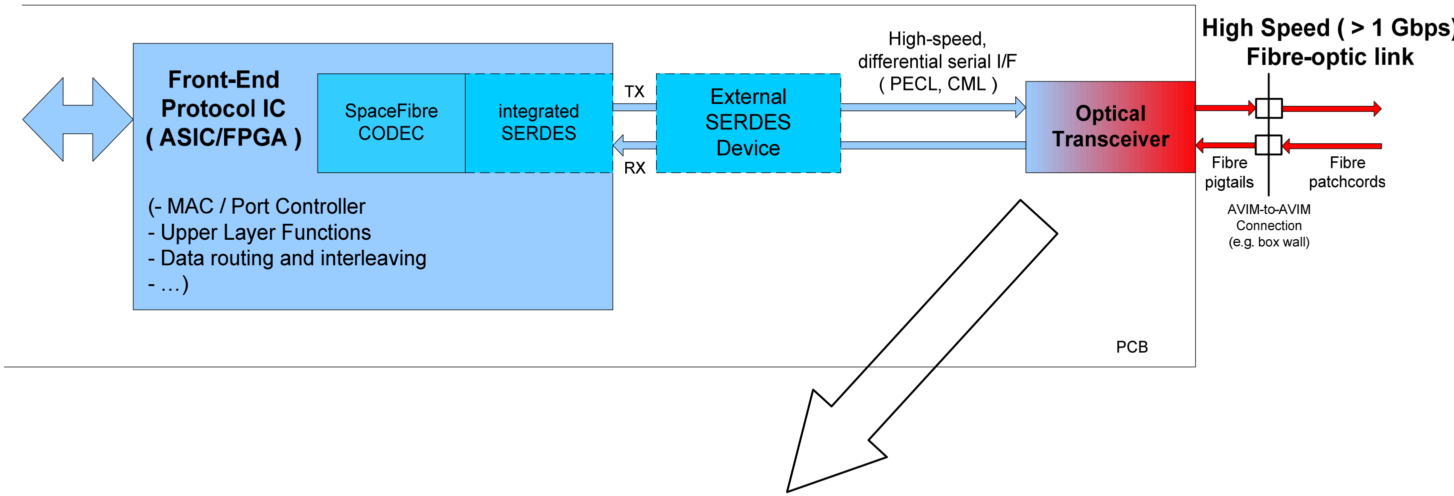
SpaceFibre Requirements

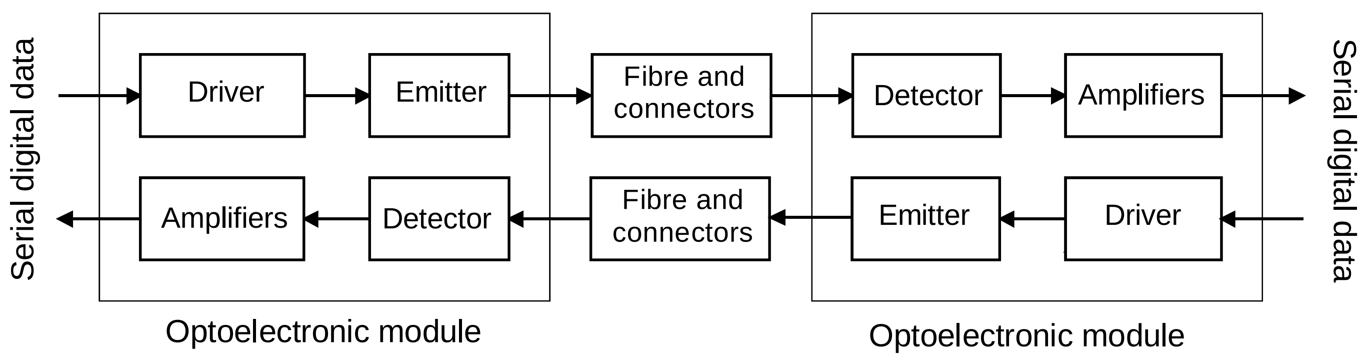
- Provide symmetrical, bi-directional, full-duplex, point-to-point communication
- 1-10 Gbps data rates over 100 m
- Bit error rate (BER) less than 10^{-12}.
- SpaceFibre link must be mechanically robust, reliable, and modular containing pluggable connectors
- Minimized size, mass and power consumption as long as reliability and tolerance to space environment is guaranteed

SpaceFibre Requirements (cont.)

- Several different missions were reviewed for identifying typical requirements to be used as the baseline for the SpaceFibre link specifications:
  - Random vibration ≤ 25 g_{rms}
  - Mechanical shock ≤ 3000 g @ 10 kHz
  - Total radiation dose ≤ 1000 Gy
  - Operational temperature –40 ... + 85 °C
  - Storage temperature –50 ... + 95 °C
  - Mission lifetime up to 15 years
  - Non-outgassing materials

SpaceFibre Link





Transceiver Module Design

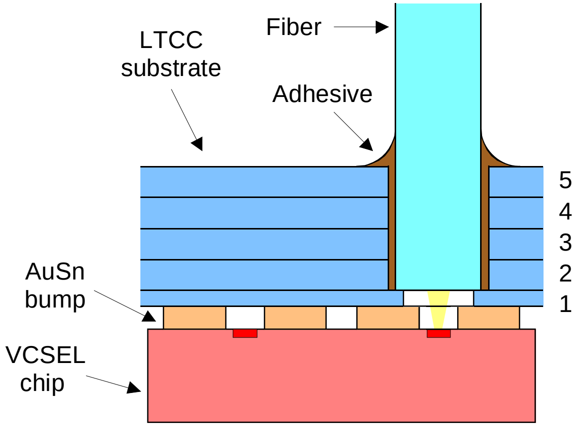
Selection of optoelectronic components:

- 850-nm vertical cavity surface emitting lasers (VCSELs)
  - low drive current and small power consumption
  - the heat dissipation of the laser and its driver is smaller than with FP lasers, which allows the transceiver module to be smaller and lighter
  - VCSELs are also easier to drive without optical power monitoring due to their smaller temperature sensitivity of emission characteristics
  - VCSELs have demonstrated good radiation tolerance
- GaAs PIN diodes
  - PIN diodes are the most common photodetectors in short-reach fibre-based data transmission
  - Si photodiodes are more sensitive to SEUs than GaAs detectors

Transceiver Module Design (cont.)

Optical design:

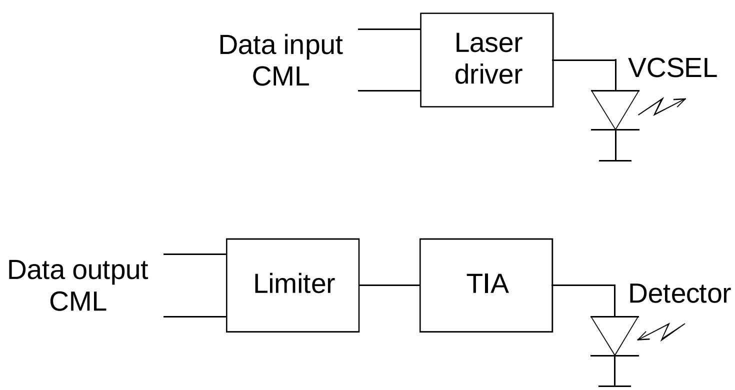
- Low temperature co-fired ceramic (LTCC) substrate technology
- The VCSEL laser chip is aligned with the substrate hole and attached using solder bumps
- The multimode fibre is passively aligned and supported using a precision hole in the five-layer LTCC substrate
- The fibre-to-detector coupling is realized using the same principle

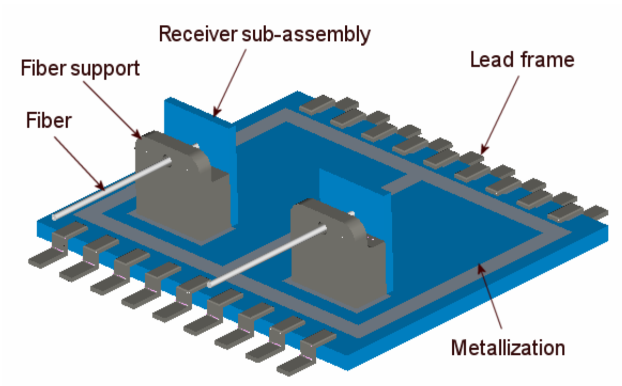


Transceiver Module Design (cont.)

Electrical design:

- Transceiver is divided into the main module and two sub-modules
- The transmitter sub-module contains the VCSEL, its driver chip and few passive components
- The receiver sub-module contains the detector, transimpedance amplifier (TIA) chip and few passives





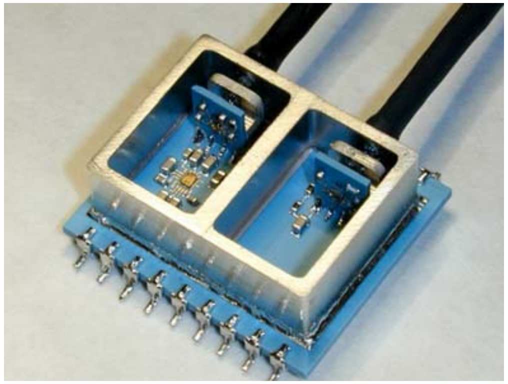
Transceiver Module Design (cont.)

- The transmitter and receiver use a single 3.3-V power supply
- Industry standard 1 x 9 output footprint with surface mounted pins.
- Employs current mode logic (CML) data inputs/outputs
- Typical power dissipation of 420 mW
- Electromagnetic interference shielding between the transmitter and receive sub-modules

Transceiver Module Design (cont.)

Packaging design:

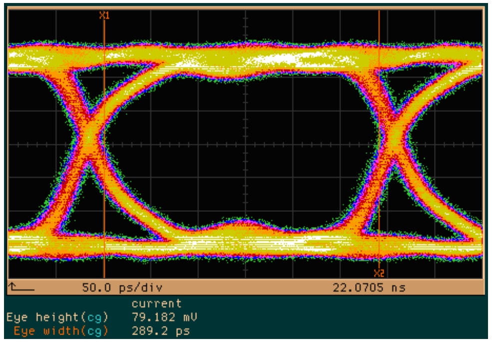
- Kovar package with a laser-welded lid
- LTCC substrates are inherently airtight
- dimensions of 8 · 22 · 25 mm^3 (thickness · length · width).
- The weight without pigtails is 8 g
- Pigtails are terminated with Diamond AVIM connectors that weigh 6 g each



Transceiver Module Testing

Functional testing:

- Measured average output power of 1.16 mW with a standard deviation of 0.13 mW
- The eye diagram at the receiver output was found to remain acceptable up to 6 Gbps
- BER testing at 2.5 Gbps showed that with 99% confidence BER is better than $1.3 \cdot 10^{-14}$. No errors were detected during the measurement period, so the BER result is expected to improve in measurements with longer duration
- The SpaceFibre link was proved to have an optical power budget margin of at least 15 dB

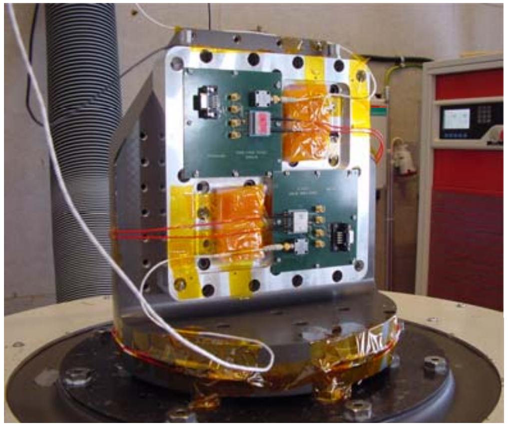


Eye diagram of the 3.125 Gbps PRBS at the receiver output.

Transceiver Module Testing (cont.)

Vibration testing:

- Four modules were tested to all three axis
- Two different test levels:
  - The intermediate level test contained four sweeps up and four sweeps down from 5 to 150 Hz with a sweep rate of 2 octaves/min. and a maximum acceleration of 20 g. This was followed by a 10-min. period of random vibrations from 20 to 2000 Hz with a total level of 15.7 g_{rms}.
  - The evaluation test was otherwise similar but consisted of two sinusoidal vibration sweeps with a maximum acceleration of 30 g, which was followed by a 6-min. period of random vibrations of 22.3 g_{rms}.
- No performance degradation was detected for any of the four transceivers after vibration testing



Transceiver Module Testing (cont.)

Shock testing:

- Four modules were tested to all three axis
- The first tested module failed from shock impacts containing an unintended 4300-g resonant peak. This was due to a shock table characteristic resonance at 1200 to 1300 Hz that could not be dampened
- For the other modules, impacts with peaks from 2900 to 3900 g were used
- All three modules were found to be operational after the shock impacts. One module showed slight degradation in performance

Transceiver Module Testing (cont.)

Thermal cycling:

- Two modules were subjected to a test campaign of 2 x 40 cycles in air circulating chamber from -40°C to +85°C.
- The average duration of min. and max. temperature levels for each cycle was 15 minutes
- Modules were operational throughout the testing, transmitting BER test data at 2.0 Gbps to both directions
- The maximum degradation of module power budget was in the order of -4 dB at + 85°C. At -40°C the performance degradation was negligible

Transceiver Module Testing (cont.)

Radiation testing:

- Envisaged critical components were laser driver, PIN diode and limiting amplifier
- Gamma and proton testing performed by SCK-CEN to four transceiver modules
  - Gamma irradiation test with offline BER measurements at incremental dose levels up to 500 kRad
  - 36 MeV and 63 MeV proton tests with offline BER measurements at incremental fluence levels
- Gamma irradiation testing confirmed the robustness of the optic transceiver modules against ionizing radiation, with only minor optical power losses up to 0.7 dB at the dose levels up to 500 kRad.
  These moderate losses can probably be attributed to radiation induced attenuation in the fibre pigtails.

Transceiver Module Testing (cont.)

Radiation testing:

- Testing at 36 MeV proton fluences up to 10^{13} protons/cm^2, revealed a more pronounced damage, mainly attributed to displacements effects
- Since the testing was done to complete transceiver modules, detailed radiation effects on component level were not monitored
- Excluding the 36 MeV proton irradiated module, all modules seem to be operating well after 6 months … 1 year after the irradiation

Table 6-1. Summary of the observed damage in the irradiated modules.

Test	Observed damage
Gamma, power on	Slightly decreased TX power, slightly decreased RX sensitivity and increased susceptibility to EM interference.
Gamma, power off	Increased susceptibility to EM interference
36 MeV proton	10 dB reduction in TX power, slightly decreased RX sensitivity and increased susceptibility to EM interference
63 MeV proton	Damaged but operational ModC input, slightly decreased RX sensitivity and increased susceptibility to EM interference

Optical Fibre Selection

- The selected optical fibre needs to be radiation hardened and capable of 10 Gbps transmission capacity over a length of 100 meters
- Phosphorous doping must be avoided as it is very sensitive to radiation
- Single-mode fibres must be avoided due to tight laser to fibre alignment tolerances
- Step-index multimode fibre must be avoided due to bandwidth limitations

⟶ With its 50-micron core diameter and large NA, the laser-optimized graded-index multimode fibre is the only option that can meet the bandwidth and light coupling requirements of the SpaceFibre link

Optical Fibre Testing

- Radiation hardness of several COTS laser-optimized graded-index multimode fibres were determined
- Measurements of the radiation-induced attenuation show losses varying from 7 to 16 dB when the 100 m long fibres are exposed to a dose rate of 450 Gy/h and for a total irradiation dose of 1000 Gy
- When considering the typical dose rates in space, radiation-induced attenuation losses can be as low as 0.05 to 1 dB
- Draka MaxCap 300 radhard-optimized fibre, the best performing fibre was selected for the SpaceFibre link

Connectors

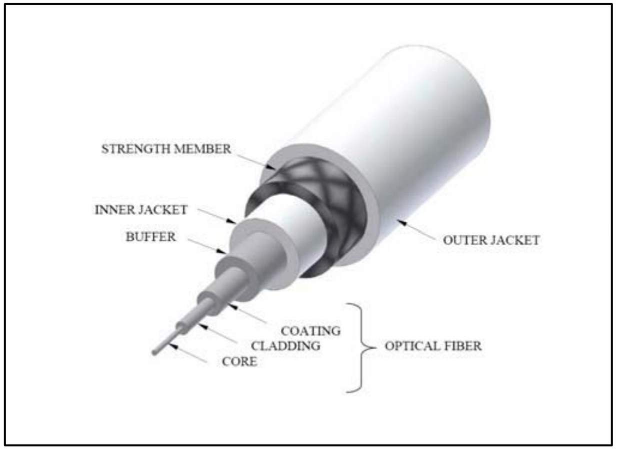
- Diamond AVIM connector was selected for the SpaceFibre link
- This connector has already been used successfully in several space missions
- The AVIM connector has been selected for several reasons:
  - Compact, low profile and lightweight
  - Excellent performance
    (typical insertion loss 0.2 dB)
  - Works for both single-mode and multimode
  - Return loss (typical < 45 dB)
  - Environmentally robust
  - No outgassing materials
  - Includes a unique ratchet style Anti-Vibration Mechanism

Cable Design

- Cables from W. L. Gore & Associates were selected for the SpaceFibre link
- Due to the wide operational temperature ranges in space, thermally-induced microbending is a real phenomenon to be managed
- An expanded polytetrafluoethylene (ePTFE) buffering system can minimize microbend-induced attenuation changes
- W. L. Gore design incorporates a layer of ePTFE directly over the coated fibre
- This layer does not influence the effect of the primary coating on the fibre, but it does significantly mitigate the coefficient of thermal expansion (CTE) effects of all other layers e.g. braids and cable jackets

Cable Design (cont.)

- Two simplex cables have been designed:
  - 1.2 mm cable may mainly be used within electronic boxes or inside a protective structure. It is smaller and has less weight.
  - 1.8 mm cable is designed for being used within the boxes as well as for the connection between boxes and shelves. It has a higher tensile strength and crush resistance.
- **The buffer** consists of a wrapped layer of ePTFE
- **The inner jacket** consists of an extruded thermoplastic layer.
- **Strain Relief** of Braided Kevlar®
- **Cable outer jacket** consists of a fluoroplastic layer



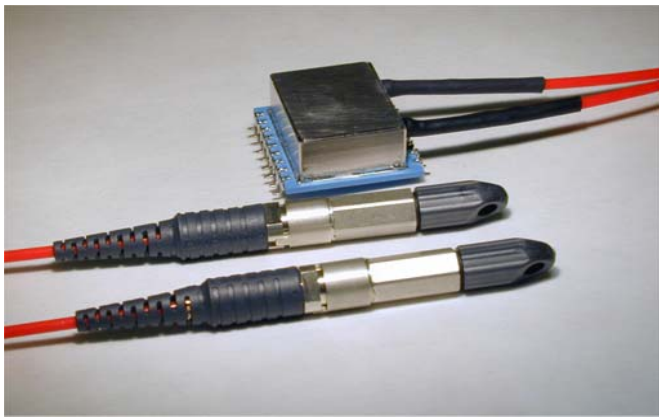
Conclusions

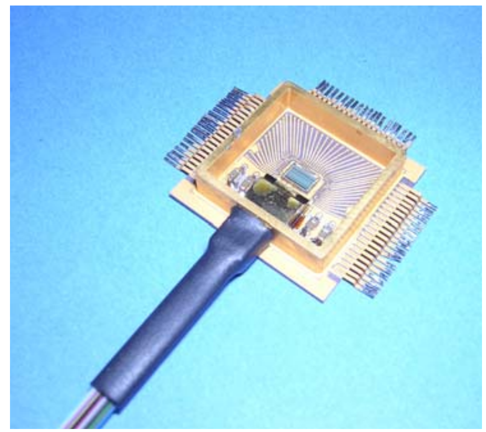
- The realized SpaceFibre optical link operates up to 100 meters at data rates from 1 to 3.125 Gbps and has a bit error rate less than 10^{-12}
- The data transfer rate can be upgraded to 10 Gbps by selecting a faster VCSEL, PIN diode and TIA
- Transceiver modules were proven to be mechanically robust
- Radiation testing confirmed the robustness of the optic transceiver modules against ionizing radiation
- In proton testing more pronounced damage was detected, which would require more in-depth analysis

Conclusions (cont.)

- The optical fibres used in the pigtails and patchcords are radiation-resistant and the AVIM connector is space-qualified
- Based on the operational and environmental test results, the system is a promising candidate for the upcoming high-speed intra-satellite networks to provide symmetrical, bi-directional, full-duplex, and point-to-point communication
- Work continues in a new ARTES-5 activity were the transceiver modules are upgraded to 6.25 Gbps and qualified to EM-level

SpaceFibre EM Model Development





Updated Requirements

- Hermetic packaging
- Link budget of 14 dB at **6.25 Gbps** at worst case +85 degC
- Max power dissipation < 400 mW
- Transceiver dimensions < 20 mm x 20 mm x 6 mm
- Transceiver mass < 5 g (without pigtails)
- Power saving modes (TBC): Active, Suspended, Quiescent, Off

Industrial Organisation

The SpaceFibre EM Model development team:

- Patria (Finland): Prime,
  Requirements specification, testing
- Thales (France): End-user,
  Requirements specification, testing
- VTT (Finland): Optoelectronics transceiver module
- D-Lightsys (France): Optoelectronics transceiver module
- Tecnologica (Spain): Component level testing,
  EM model qualification testing
- Fibrepulse (Ireland): Fibre optic pigtails

Project Tasks

- Two different transceivers will be developed and tested:
  - Upgrade and re-design of the VTT developed SpaceFibre transceiver prototype
  - Upgrade of D-Lightsys optoelectronic devices already designed for harsh environments
- Post-production functional testing by VTT & D-Lightsys
- End-User testing by Thales
- SpaceWire – SpaceFibre network testing by Patria
- Evaluation test campaign by Tecnologica
  - Components evaluation
  - Transceivers EM evaluation

Development Schedule

- Preliminary design phase started
- Critical Design Review Q4/2008
- Final Delivery Q2/2009

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