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# *Mass-reduction of high-speed spacecraft datalinks enabled by rugged photonic transceivers*

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# Mass reduction of high-speed spacecraft data links enabled by rugged photonic transceivers

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## ABSTRACT

In this paper, we first review the advantages in mass, loss and bandwidth of fiber optic links compared to coax for the fiber-optic physical layer of high-speed digital datalinks on spacecraft. We then report the results of ongoing development of commercial-off-the-shelf photonic transceiver components designed to meet spacecraft physical layer fiber optic datalink requirements. Results are presented detailing the performance and reliability of photonic transceiver modules, as well as radiation exposure tests (gamma, neutrons, protons and heavy ions) for these modules. The results show that these modules meet or exceed many of the requirements of spacecraft applications, and indeed they are being considered for or deployed on various spaceflight applications.

Keywords: SpaceWire, SpaceFibre, Spacecraft Datalinks, Spacecraft Electronics, Spacecraft Photonics, Avionics.

## 1. INTRODUCTION

Optical fiber is an ideal medium for high-speed signal transmission on space platforms, since optical fiber cables support data rates up to many 10s of Gbps, are much lighter and smaller than copper coax cables of equivalent bandwidth and length, and are immune to radio-frequency (RF) interference from adjacent cables, so they require no heavy RF shielding. Ground-loop issues are also reduced due to the natural electrical isolation provided by non-metallic fiber-optic cable assemblies.

Fiber optic cable solutions exist for spacecraft applications, however, the availability of suitable photonic transceiver components for space applications has not been widespread. The major manufacturers in the photonics industry are typically not able or willing to address the highly-specialized requirements, long design cycles, extreme environmental robustness, ultra-high reliability, traceability, radiation tolerance and small, inconsistent production volumes encountered with space applications. We believe this combination of factors has limited the adoption of photonic links on spacecraft, while multi-gigabit links have proliferated in non-space aerospace applications for many years.

We therefore undertook development of photonic transceivers designed to address the increasing data transmission requirements between avionics modules onboard spacecraft. This growth is driven by the use of processors with high-speed serial data I/O to support the growing data requirements of advanced sensor systems and increased bandwidth of communications switches and satellite communications terminals.

In previous papers[1,2], we discussed the development and test results of photonic transmitters, receivers and transceivers for aerospace applications, and highlighted the challenges with spacecraft transceiver design. In this paper we will first briefly review the benefits in terms of size, mass and bandwidth afforded by utilizing optical fiber instead of copper cabling for multi-gigabit data networks on spacecraft. We will then describe the design of rugged photonic transceiver components for aerospace applications and then summarize the results of gamma, neutron, proton and heavy ion radiation testing performed on the transceiver components.

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## 2. COMPARISON OF COPPER AND FIBER OPTIC LINKS

In this section we illustrate some of the advantages of fibre optic cabling compared to copper-based coax cables for spacecraft interconnects by way of a practical example. We consider a digital serial datalink operating at 1 Gbps up to 10 Gbps between two modules on a spacecraft using the SpaceFibre data networking protocol standard. In this link, the serial differential digital current-mode-logic (CML) signals are to be sent in both directions between Module 1 and Module 2. As illustrated in the block diagram of Figure 1, and according to the SpaceFibre draft standard, this can be accomplished in two ways:

1. Using four copper coax cables (two coaxes for each of the 100-ohm differential signal pairs), or
2. Using two fiber optic links (one fiber for each signal path).

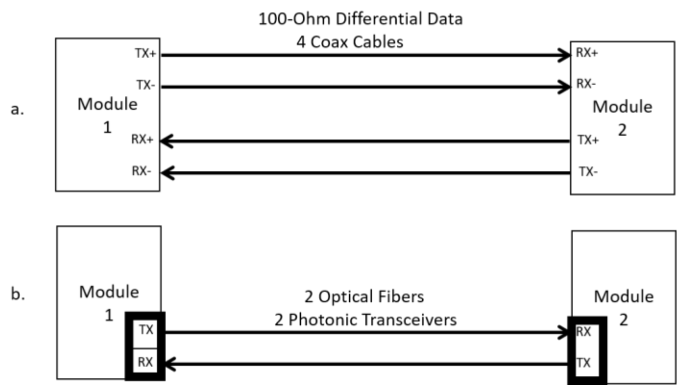


Figure 1. Comparison of SpaceFibre physical layer interconnect options:
a. four coax cables,
b. two optical fibers and two photonic transceivers.

In the case of the coax link, it is assumed that the signal level introduced to the coax corresponds to the standard for CML at 800-1200mV, with minimum input signal level of 200 mV required for the CML receiver at the output of the coax. This corresponds to a maximum permissible loss of 12 dB over the frequency band corresponding to the digital signal frequency content, specified as 0 GHz for a 10 Gbps signal. This consideration drives the choice of coax cable type to minimize mass according to the length of the link in question. For SpaceFibre cabling as specified in the draft standard (Axon AW 2.2), the mass of the four cables is 48 g/m, the diameter of each cable is 2.4mm, and the loss at 10 GHz is 3 dB/m. For low-loss space-grade cable (such as Gore Type-21), the mass is higher at 228 g/m, the diameter is 4.8 mm, but the loss is lower at 0.3 dB/m.

By comparison, the fiber optic links require two fibers per link with mass of 10 g/m, diameter of 2 mm per jacketed simplex fiber, and the loss of the link is fully compensated by the photonic transceiver electronics to generate a full-amplitude CML signal at the end of the link. It is also possible to configure both fibers into one jacket, since the diameter of the optical fiber buffer is just 250 microns. Using two separate optical fiber jackets is a “worst case” assumption, and the mass could be reduced further if both fibers were contained in a single jacket. The photonic transceivers required at each end of the link each have mass of 5 g, and circuit board footprint of approximately 2 cm x 2 cm.

Figure 2 illustrates the relative size and mass of the three types of cable. Figure 3 illustrates the cable loss vs length at 10 GHz.

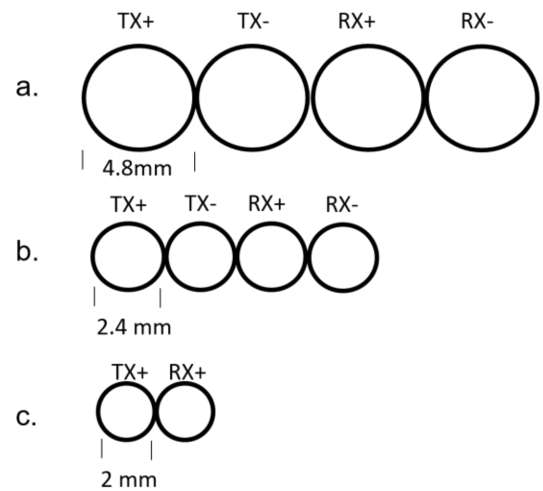


Figure 2. Comparison of interconnect solutions:
a. Gore Type 21 coax cable: 223 g/m, 4.8mm diameter;
b. SpaceFibre Type-A coax cable: 48 g/m, 2.4 mm diameter;
c. Jacketed optical fiber simplex cables: 10 g/m, 2 mm diameter.
Note: Two separately-jacketed fibers are shown, but both fibers could be contained in a single jacket.

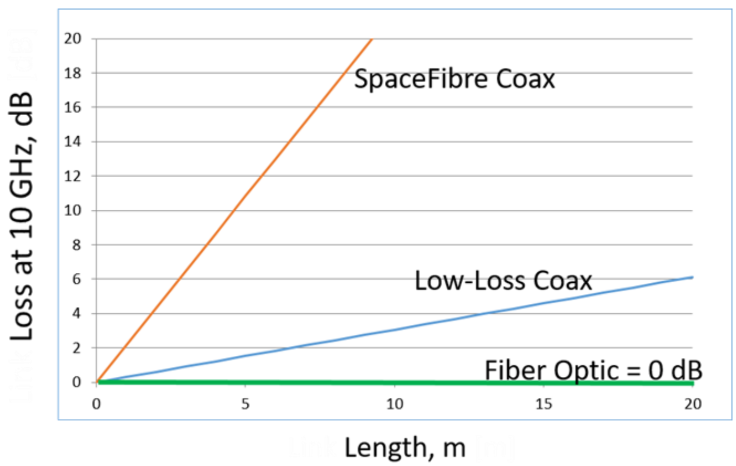


Figure 3. Loss in dB at 10 GHz for SpaceFibre Type-A coax, Gore Type-21 low-loss coax, and fiber optic link.

The SpaceFibre specification permits up to 2 dB loss per connector at each end of the link. Therefore, we must add 4 dB to the losses shown in Figure 3 for the SpaceFibre and Gore coax link. This means that the SpaceFibre coax link has a maximum length of approximately 3.5 meters before it reaches the maximum permissible loss of 12 dB. The Gore Type-21 cable would support much longer links in excess of 20 meters.

The fiber optic link is essentially "lossless", due to the regeneration of the signal in the receiver circuit to a full CML output level of 800 mV p-p. This holds true provided the optical power incident on the photodiode is above the minimum sensitivity threshold for error-free transmission. The SpaceFibre draft standard specifies this minimum optical level to be -16 dBm for 5 Gbps link, and -11 dBm for a 10 Gbps link. This means a fiber optic transceiver could in principle support essentially any length link on a spacecraft, up to 400 meters at 10 Gbps if OM4 fiber is used.

Figure 4 illustrates the cable mass as a function of cable length. Table 1 summarizes the results of comparing the three implementations of the SpaceFibre physical layer. The much-lower fiber optic cable mass of 9.6 g/m, compared to 48 g/m for SpaceFiber Type A cable or 223 g/m for low-loss Gore Type-21 coax, results in greatly reduced overall physical layer mass compared to the coax solutions. The fiber optic cable mass could be essentially halved if a single jacket is used for both fibers, resulting in total mass of 28.6 g for the fiber optic link.

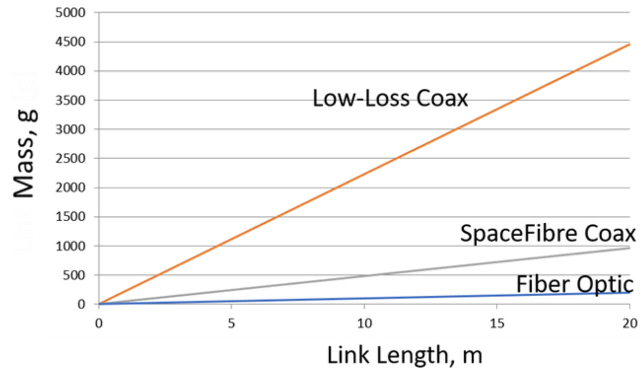


Figure 4. Cable mass vs length. Note that electrical or optical connectors are not included.

| | Low-Loss Coax<br>Gore Type 21 Space-grade | SpaceFibre Coax<br>(Axon AW2.2) | Fiber Optic<br>2 mm jacketed with 2 XCVR |
|---|---|---|---|
| Cables required | 4 | 4 | 2 |
| Loss | 0.9 dB | 6.4 dB | 0 dB |
| Cable mass (no connectors) | 223 g/m | 48 g/m | 9.6 g/m |
| Optical XCVRs | 0 | 0 | 9.4 g  |
| 3-meter total mass | 670 g | 144 g | 38 g |
| Power consumption | 0 | 0 | 0.8 W |

Table 1. Summary of cable loss and mass at 10 GHz for a 3-meter link. Fiber optic cable mass (g/m) could be halved if a single jacket is used for both fibers, resulting in total mass of 28.6 g for the fiber optic link. Electrical and optical connectors not included in mass.

## 3. FIBEROPTIC TRANSCEIVER RADIATION TESTING

In a previous paper[2], we reviewed the design of photonic transceivers, which have two main sub-components: laser transmitter and photodiode receiver. The function of the transmitter is to convert electrical serial data bits to optical pulses, and the photodiode receiver converts optical pulses to electrical serial data bits. These functions are realized in multi-gigabit systems using opto-electronic semiconductor devices (GaAs vertical cavity surface emitting laser (VCSEL) diodes and planar photodiodes at 850 nm) and SiGe BiCMOS electronic integrated circuit (IC) amplifier and control-loop devices.

Three form-factors were developed, including Size 8 optoelectronic contacts and printed-circuit-board mountable transceiver modules. All form-factors utilize the same circuit schematic and identical optoelectronic and electrical driver and controller devices. A wide range of environmental and reliability testing was performed on these devices and is summarized in a previous paper[2]. These devices are shown in Figures 5-8.

The devices developed utilize a highly-simplified circuit approach with no microprocessor or memory devices in the units, so as to minimize susceptibility to radiation-induced single-event upset (SEU), single-event latch-up (SEL), etc. The Size #8 contacts and board-mountable transceivers were tested for resistance to radiation exposure in excess of 170 Krad total ionizing dose (TID) of gamma radiation from a cobalt-60 source, and 2.5 x $10^{12}$ neutrons/$cm^2$ of neutron irradiation. The units were operated with continuous data at 1.25Gbps and real-time bit-error monitoring, with no errors detected. Testing of the units conducted after the gamma and neutron exposures showed that the devices still met original specifications, and exhibited no appreciable degradation of performance.

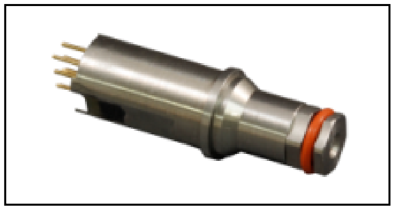

Figure 5. Opto-Electronic Contact.

Figure 6. Size #8 contacts in panel-mount avionics connectors: D-sub (upper) and D38999 (lower).

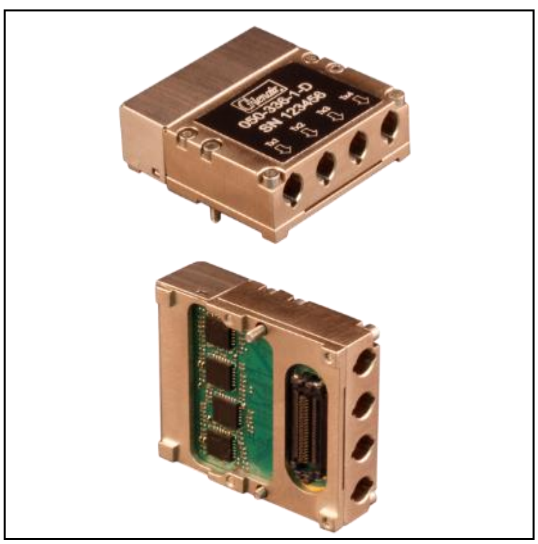


Figure 7. PCB-mountable quad-output transmitter unit with ARINC 801 optical interface: Top view (upper) and bottom view (lower). Note: units are pictured without fiber optic connectors attached.

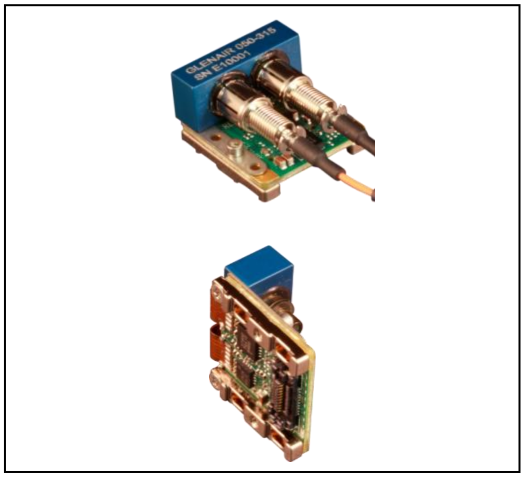

Figure 8. Two-fiber PCB-mount transceiver form-factor. Top view with fiber optic connectors attached (upper) and bottom view showing electrical board-mount high-speed connector interface at front edge (lower.)

Proton irradiation testing with 250 MeV protons from a synchrotron source was then conducted on the Size 8 contacts. Proton testing was performed at the Loma Linda University Medical Center (LLUMC) in conjunction with a third party. The testing was performed using the LLUMC synchrotron which provided periodic beam spills of 250 MeV protons incident on the Tx and Rx. The Tx and Rx were mounted on an evaluation card and oriented such that they were irradiated simultaneously during the testing.

During the testing a Bit Error Rate Tester (BERT) generates a 1.25 Gbps PRBS7 pattern that is input into the Rx under test and which then outputs to the Tx under test. The Tx finally outputs the pattern back to the BERT where it is compared to the expected PRBS7 pattern. If any mis-compares are observed, they are logged. These mis-compares observed during irradiation are attributed to Single Event Upsets (SEU) resulting in data errors and contribute to the overall Bit Error Ratio (BER) calculated at the end of each run.

The observed SEU resulting in bit errors generally occurred during the beam spills and were typically isolated single bit error events, i.e. not burst events. During proton testing two radiation induced anomalies were observed resulting in a functional interrupt to the devices under test (DUTs). Additional analysis of these Single Event Functional Interrupt (SEFI) events is in process. The SEU events observed demonstrated little variance in their per-run fluence averaged cross-sections as can be seen in Figure 5. As only 2 SEFI events were observed, statistics are limited, but it is expected they would be rarely observed even in proton rich environments.

During the testing parts were irradiated with 250 MeV protons resulting in an accumulated Total Ionizing Dose (TID) of ~450 krad(Si). A plot of the SEU cross-sections as a function of dose indicates negligible increase in SEU sensitivity as a function of accumulated TID as shown in Figure 10. The statistics on SEFIs were too low for evaluation. The SEU cross-section vs. accumulated TID results are plotted in Figure 10, overlaid by a linear-fit trend-line showing negligible change over accumulated TID.

Heavy ion radiation testing was also performed on the parts, with exposure up to 84 MeV LET and no unrecoverable errors. More data on this testing will be reported at the conference and in future publications.

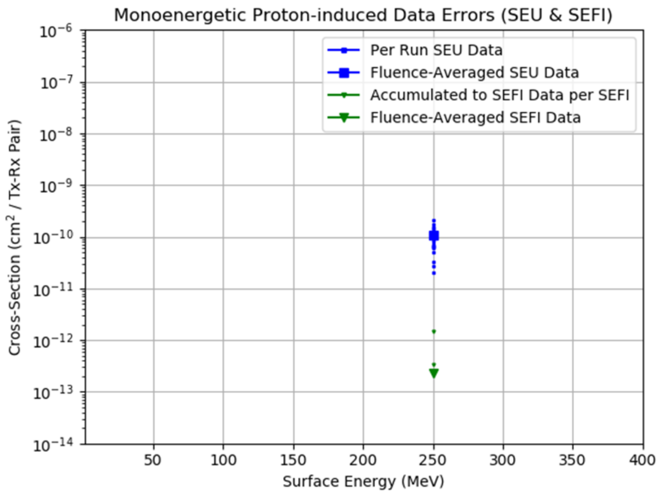


Figure 9: SEU and SEFI cross-sections for 250 MeV protons.

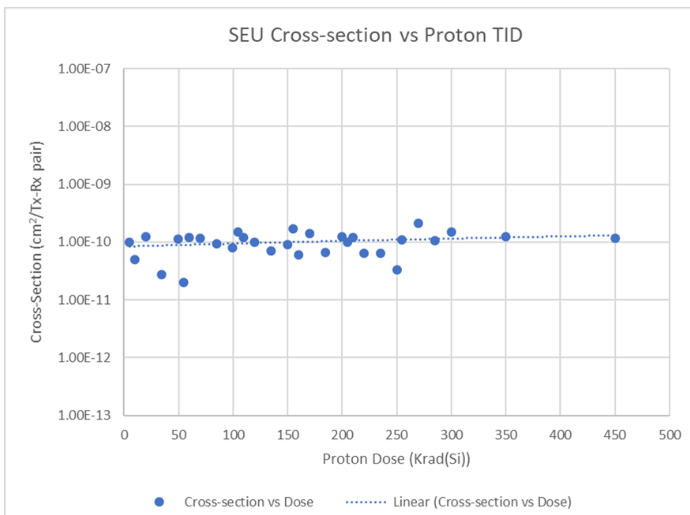


Figure 10: SEU Cross-sections as a Function of Accumulated TID.

## 4. PARALELL OPTICAL TRANSCEIVER

Many benefits in size and mass can be obtained by moving from individual optical contacts, connectors and cabling to multiple-fiber "ribbon cable". A multi-fiber D38999-style connector utilizing a 12-fiber "MT" contact is illustrated in Figure 11. Such a connector solution is envisioned by the SpaceFibre standard, and requires suitably rugged parallel optical transceivers to efficiently make use of all of the fibers.

The SpaceFibre standard provides for multi-lane "parallel optical" transceivers in addition to single-lane devices, up to rates of 10 Gbps. We developed rugged 10 Gbps parallel optical transceivers equivalent to the commercial QSFP+ standard, but ruggedized by utilizing a hermetically-sealed hybrid optoelectronic microcircuit assembly and active optical alignment process, pictured in Figure 12. This construction provides for enhanced optical output power per lane of up to +2 dBm at 850nm and sensitivity of -12 dBm typical at 10 Gbps, leading to optical link budgets of up to 14 dB.

The units incorporate an integrated heating element for the VCSEL laser arrays to permit high-performance operation over the temperature range of -40C to +85C, and can support data rates up to 14 Gbps per lane. 25 Gbps-per-lane parts are in development.

Figure 11: D38999 connector with a single MT contact (upper) and four MT contacts (lower).

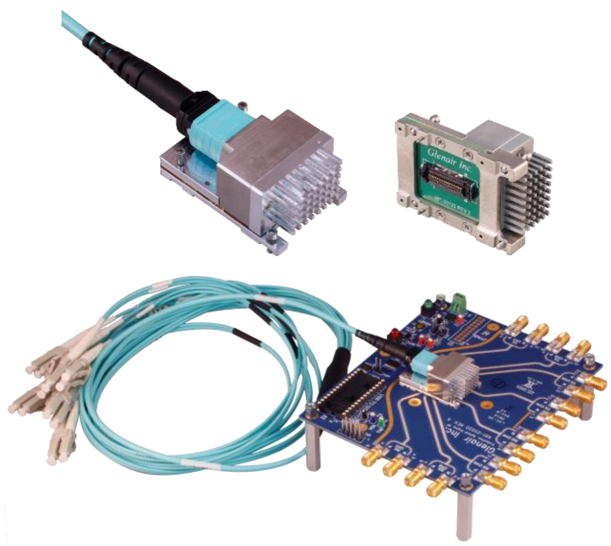


Figure 12: Aerospace-grade parallel optical transceiver: top view with MTP optical cable inserted (upper left), bottom view showing high-speed electrical connector interface (upper right), transceiver mounted to evaluation board (lower).

The transceivers utilize an MTP optical connector that is specially modified to provide enhance vibration and shock survivability. The parts interface with the host board via a high-speed board-to-board connector with proven performance. These parts have high reliability in excess of 1M hours at 50C based on FIT rate data for the lasers, photodiodes and other integrated circuits contained in the part.

They have been subjected to operating shock and vibration levels per MIL-STD-883 of 650 G 1 msec shock, 10 pulses in each axis and 46 Grms random vibration, 2 hours per axis. The hermetically-sealed units also pass MIL-STD-883 helium leak rate testing as well as 10-day humidity testing with thermal cycling. For space applications, the removable finned heatsink pictured in Figure 12 can be replaced with a conduction-cooling heatsink that will reach to a conduction surface. The units were exposed to all of these tests while operating and bit errors were monitored at 5 Gbps. No errors were detected during any of these exposures. Heavy ion radiation testing was conducted on these devices up to 64 MeV LET, with no unrecoverable events. Extension of the bit rate to 28 Gbps per lane is in process.

## 5. SUMMARY AND CONCLUSIONS

We presented an analysis that details the advantages of fiber optic interconnects for spacecraft high speed digital datalinks compared to copper coax cable implementations. We developed compact, rugged, opto-electronic transmitters, receivers and transceivers in a variety of form-factors, including parallel optical format, and subjected them to various tests, including thermal cycling, high vibration and shock, and gamma, neutron, proton and heavy ion radiation, and found them to have excellent performance. Testing to date indicates that these parts can satisfy the environmental requirements of spaceflight applications. Further testing is ongoing, as well as extension to 28 Gbps per channel, and results will be reported in future publications.

## REFERENCES

[1] R. T. Logan Jr. and D. Basuita, Proc. of International Conference on Space Optics, Biarritz, 2016.
[2] R. T. Logan Jr., Proc. of International SpaceWire Conference, Yokohama, October 2016.