DOI: 10.13009/EUCASS2017-677

Multi-gigabit photonic transceivers for SpaceFibre data networks

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Abstract

We present an analysis demonstrating how fibreoptic datalinks can greatly reduce the mass of multi-gigabit datalinks onboard spacecraft compared to traditional copper-based cabling. We developed a variety of rugged photonic transceiver components, and also discuss the details of their construction and the results of reliability and environmental tests performed on them.

1. Introduction

Data transmission requirements between avionics modules onboard spacecraft continue to increase, 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. Data rates exceeding many 10s of gigabits per second (Gbps) are needed onboard spacecraft. 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 wiring of equivalent bandwidth, and are immune to radio-frequency (RF) interference from adjacent cables, so therefore 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. We will compare and contrast the mass of fiber optic cables.

The emerging SpaceFibre standard for spacecraft networking anticipates the use of high-speed serial copper or fiber optic transmission between avionics modules and subsystems on spacecraft at serial data rates up to 10 Gbps [1]. Fibre optic cable solutions exist, however, the availability of suitable photonic transceiver components for space applications is not 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. Conversely, the development of suitable photonic transceiver hardware is typically beyond the engineering or budget capacity of most spacecraft programs. 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. We therefore undertook development of photonic transceivers designed to address the emerging aerospace requirements.

In this paper we will first briefly review the benefits afforded by utilizing optical fiber instead of copper cabling for multi-gigabit data networks on spacecraft. Then we will discuss the components of photonic transmitters, receivers and transceivers, and highlight the challenges with spacecraft transceiver design. We then describe the approach to design of rugged photonic transceiver developments and the results of performance and environmental tests appropriate for space avionics applications.

2. Comparison of copper and fibreoptic datalinks

In this section we illustrate some of the advantages of fibreoptic 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 fibre for each signal path).

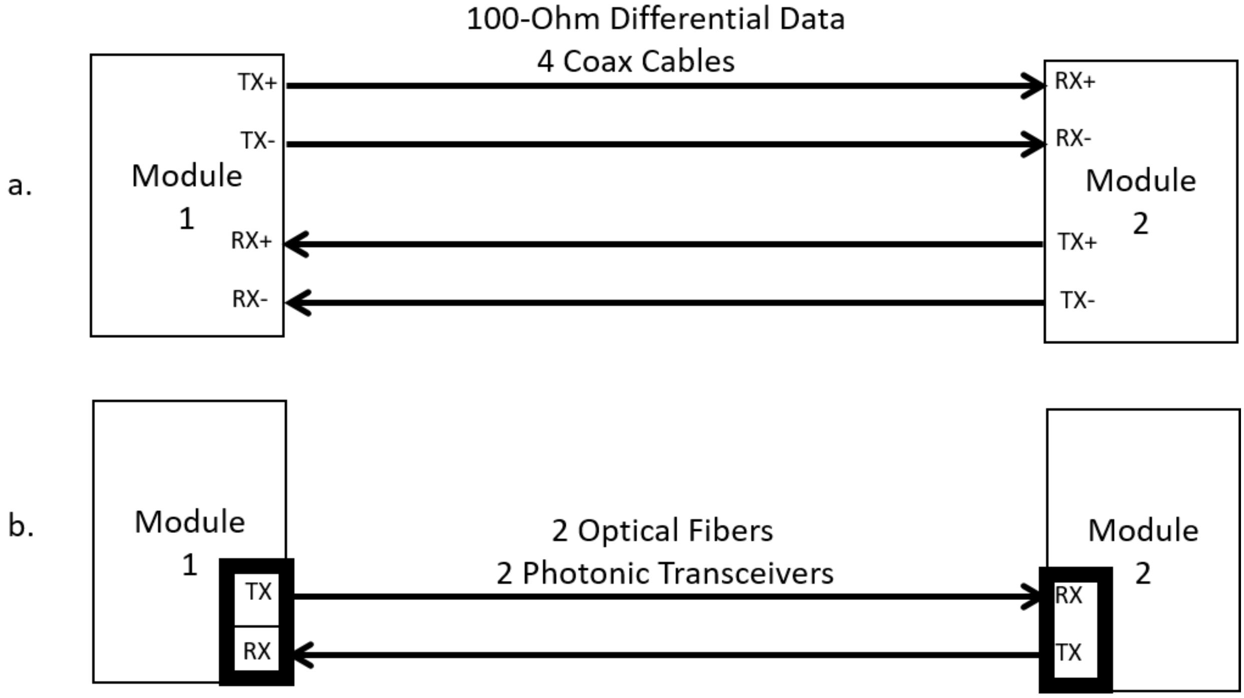

Figure 1. Comparison of interconnect solutions in terms of relative cross-sections and total mass:
a. Gore Type 21 low-loss space-grade coax cable 223 g/m,
b. SpaceFibre coax cable 48 g/m,
c. fibreoptic cable 10 g/m.

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 for the CML receiver at the output of the coax. This corresponds to a maximum loss of 12 dB over the frequency band corresponding to the digital signal frequency content, specified as the 10 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 fibreoptic 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-

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amplitude CML signal at the end of the link. 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, and Figure 4 illustrates the cable mass as a function of cable length.

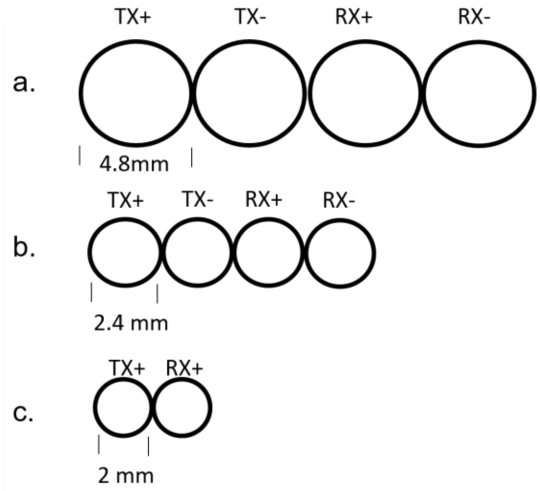

Figure 2. Comparison of interconnect solutions in terms of relative cross-sections and total mass:
a. Gore Type 21 low-loss space-grade coax cable: 223 g/m, 4.8mm diameter;
b. SpaceFibre coax cable: 48 g/m, 2.4 mm diameter;
c. Fibreoptic cable: 10 g/m, 2 mm diameter.

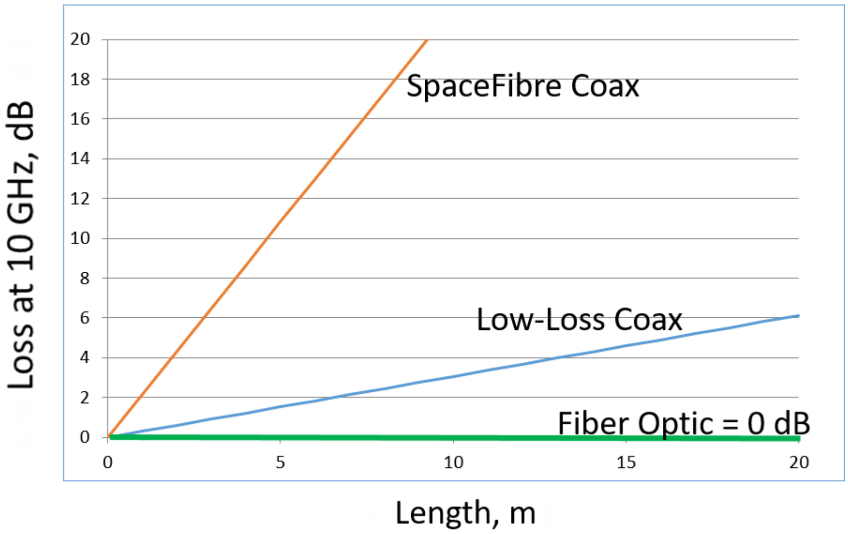

Figure 3. Loss in dB at 10 GHz for SpaceFibre coax, Gore Type-21 low-loss coax, and fibreoptic link.

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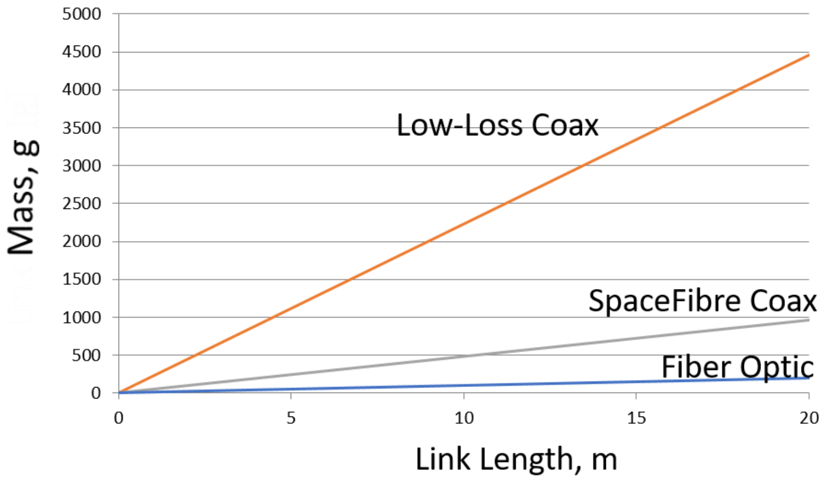

Figure 4. Cable mass vs length.

	Low-Loss Coax Gore Type 21 Space-grade	**SpaceFibre Coax** (Axon AW2.2)	**Fiber Optic** 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.

2. Overview of Photonic Transceiver Design

We next briefly review 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 (laser diodes and photodiodes) and electronic integrated circuit (IC) amplifier and control-loop devices.

The transmitter employs a laser diode which is current-modulated to impress the electrical serial data onto an optical signal as a series of on and off states. Laser diode threshold current and modulation efficiency are strong functions of temperature. Many transmitters incorporate a power monitor photodiode to sample and measure the laser output power and maintain the average output power at a constant level using a feedback loop with the average laser current as a control point.

The electronic driver IC amplifies the electrical bit stream from standard logic-levels such as Common-Mode Logic (CML) typically used as I/O to and from microprocessors, field-programmable gate-arrays (FPGAs), etc., to the level required to modulate the laser current to achieve optical modulation at the optimum level. Since the optical modulation vs bias-current slope efficiency is also a function of temperature, a second control system is used to maintain proper optical modulation over the operating temperature range. Careful matching, calibration and tuning of the bias control and modulation control circuits are required to insure that high-speed transmitters at multi-gigabit

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rates operate within industry-standard specifications over temperature. There are variations on these approaches, but what is always true is that some form of control of the laser current and modulation depth is required if the laser temperature will vary in operation.

The receiver contains a PIN photodiode, transimpedance amplifier IC, and limiting amplifier IC. The transimpedance amplifier often contains an AGC circuit to maintain the output level in an acceptable range when higher-level optical input signals are present. The limiting amplifier may also contain a bandwidth-limiting element to improve noise performance at lower bit rates.

For bit rates up to 10 Gbps, the above laser diode, photodiode and IC components are available that operate from -40C to +85C without external thermal controls. Manufacturers of commercially-available lasers, photodiodes and transceiver electronic ICs do not typically have test data for the performance of their devices in radiation environments. This is a central challenge to realizing photonic transceivers for space applications.

3. Technical approach

Most modern datacom transceivers and IC chipsets contain CMOS circuitry and memory to support bias control lookup, serial I/O monitor and control ports, etc. to conform to datacom networking interface standards. However, these transceiver products are typically board-mountable units that accept commercial-grade optical connectors, and do not need to operate in the harsh aerospace environment, including radiation. As such they are not typically suitable for use in space. In order to be suitable for aerospace applications, appropriate aerospace-grade connectors need to be accommodated and the semiconductors must withstand the radiation exposure levels.

One example of an optical transceiver form factor that satisfies many of these requirements is shown in Figure 5, called a Size #8 opto-electronic contact. These devices provide electro-optic conversion of high-speed data signals from electrical to optical format, or optical to electrical format, inside of a fiber-optic connector on an avionics module in standard size #8 connector cavities. Because of the very small package size (~20 x 6.5 mm), we developed opto-electronic circuits using very simple IC chip sets that provide only basic monitor and control I/O signals such as “transmitter enable”, “transmitter fault” and “receiver loss of signal (LOS).” The focus of the development was on fitting into the allotted form-factor, strictly complying with ARINC 801 optical contact float requirements, and surviving harsh aerospace environments.

These transmitter and receiver contacts may be inserted into ARINC 400 or 600 avionic-bay connectors, or into special front-insert D38999 or D-sub connectors (see Figure 6), to provide data translation between electrical and optical domains inside of a panel-mount connector on an avionics module. The optical fiber interface of the ARINC 801 fiber optic contact used supports repeated blind-mating due to the incorporation of a floating optical ferrule, by using a unique design that incorporates a flexible circuit board assembly internal to the unit [2].

The transmitter contact utilizes a hermetically-sealed GaAs VCSEL and the receiver a hermetically-sealed GaAs photodiode at 850nm with a multi-mode ARINC 801 fiber optic interface. The optical interface to the cable is accomplished using a mating adapter insert in the plug Size 8 cavity that accepts a standard ARINC 801 optical contact. These opto-electronic contacts can support data rates from 50 Mbps to 5 Gbps, and interface with standard Common-Mode-Logic (CML) differential data signal levels on the electrical inputs and outputs. They operate from 3.3 V input power, consume ~60 mA of current, and have a transmitter enable input, as well as transmitter fault and Loss of Signal (LOS) output status discrete signals. The optical interface specifications conform to the output power levels, eye-mask-margins, extinction ratios, and receiver sensitivity typical of industry-standard Fiber Channel and Gigabit Ethernet specifications, so the optical ports will interface via standard 50/125 micron or 62.5/125 micron multimode optical fiber with other commercial datacom optical transceivers as might be encountered in ground test equipment.

Figure 5. Opto-Electronic Size #8 Contact.

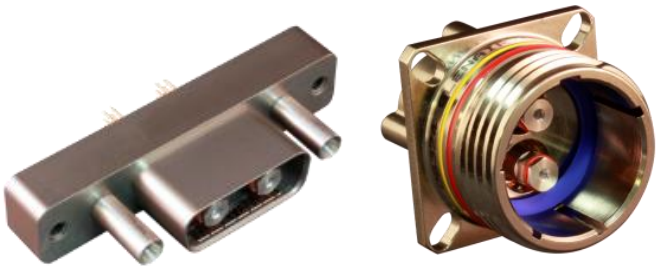

Figure 6. Size #8 contacts in panel-mount avionics connectors: D-sub (left) and D38999 (right).

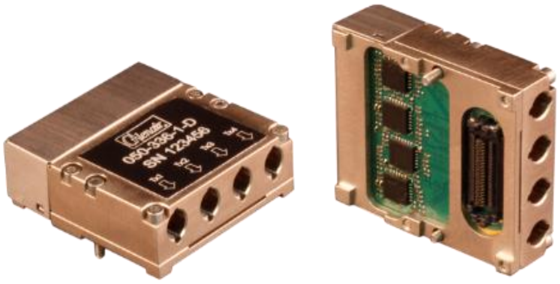

Figure 7. PCB-mountable quad-output transmitter unit: Top view (left) and bottom view (right).

In addition to the Size #8 contacts, the same optical and electrical device circuits have been incorporated into printed-circuit-board (PCB) mountable transceivers as shown in Figures 7 and 8. These devices utilize a high-speed surface-mounted PCB connector on the bottom of the unit to provide the connectivity to the host PCB via 100-ohm differential CML data streams, and are affixed using captive screws to threaded inserts that are soldered into the host PCB. The four optical interfaces of the four-fiber version in Figure 7 are machined cavities that strictly conform to the ARINC 801 standard, with retaining clips to hold the contact that require the use of an extraction tool for contact removal.

The two-fiber form-factor shown in Figure 8 utilizes a new connector developed by Glenair (Glenair GC-type) that has extremely low mass, low protrusion and very high tolerance to shock and vibration. This connector and transceiver permit a small footprint to be consumed on the customer PCB, and are much smaller than a standard datacom SFP pluggable transceiver, as shown in Figure 9.

One benefit of a simplified circuit approach is that there are no microprocessor or memory devices in the units, which are typically more susceptible to single-event effects (SEE), latch-up, etc.

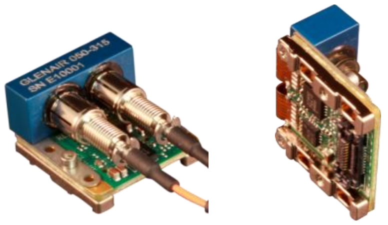

Figure 8. Two-fiber PCB-mount transceiver form-factor. Top view (left) and bottom view (right.)

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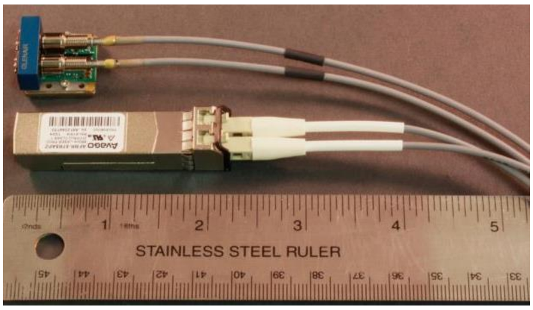
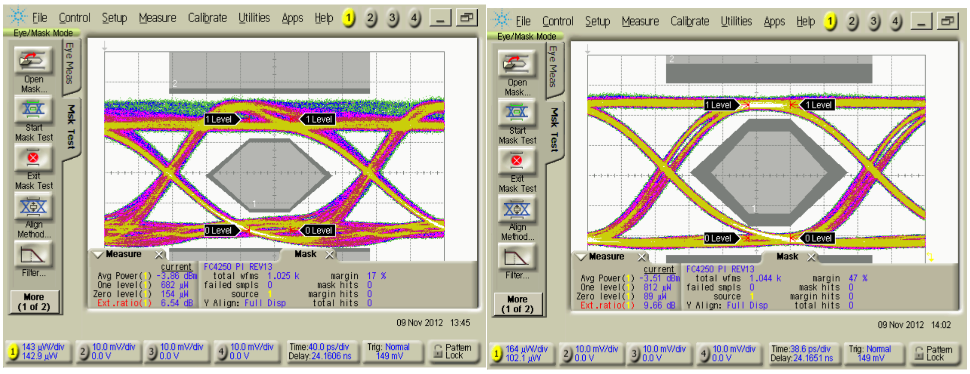


Figure 9. Size comparison of Glenair 2-fiber transceiver with commercial datacom SFP pluggable transceiver.

4. Test results

Various reliability and qualification tests were conducted on the parts described above. Some key results are summarized here.

The filtered transmitter eye diagram at 4.25 Gbps for the Size #8 contacts at various temperatures is shown in Figure 10, showing stable optical power, acceptable eye-mask margins and extinction ratios over the -40C to +90C range of ambient operating temperature. The performance of the other transceiver form-factors is similar, since they use the same circuit schematic and components. The eye-mask testing was performed at 4.25 Gbps due to the availability of test equipment with this data rate filter. The links tested using these devices also run error-free at 5 Gbps.



```
current                   FC4250 PI REV13
Avg Power(1) -3.86 dBm     total wfms  1.025 k        margin  17 %
One level(1) 682 µW       failed smpls 0            mask hits  0
Zero level(1) 154 µW            source 1           margin hits  0
Ext.ratio(1) 6.54 dB      Y Align: Full Disp        total hits  0
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```
current                   FC4250 PI REV13
Avg Power(1) -3.51 dBm     total wfms  1.044 k        margin  47 %
One level(1) 812 µW       failed smpls 0            mask hits  0
Zero level(1) 89 µW             source 1           margin hits  0
Ext.ratio(1) 9.66 dB      Y Align: Full Disp        total hits  0
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-40C +90C

Figure 10. Size #8 contact filtered eye diagrams at 4.25Gbps.

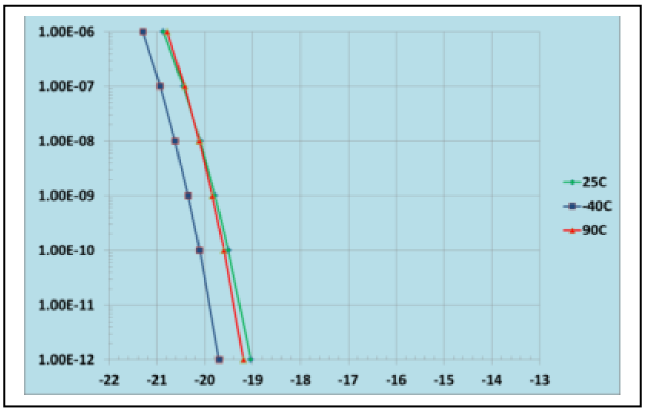

Figure 11. Receiver sensitivity at 4.25Gbps.

The receiver sensitivity typical for the Size #8 opto-electronic contact measured at 4.25 Gbps at various temperatures is shown in Figure 11. As evident in the figure, there is approximately -19 dBm, which is 5 dB of margin beyond the

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Fiber Channel standard specification for 4.25 Gbps of -14 dBm. Given the transmitter output power of approximately -3.5 dBm, this yields an optical link budget of greater than 16 dB at 4.25 Gbps.

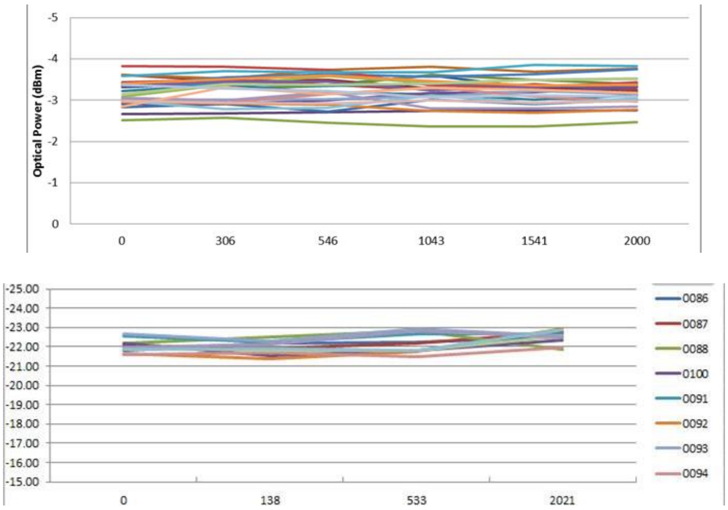

Figure 12. Accelerated aging of Size #8 opto-electronic contacts. Transmitter output power (top) and receiver sensitivity at 1.25 Gbps (bottom).

Accelerated aging tests were performed on 20 transmitter and receiver devices while operating at +85C, and the results are shown in Figure 12. No failures were observed. Temperature cycling testing was also performed for 1000 cycles from -55C to +125C, non-operating on the PCB-mount transceivers and the Size #8 contacts. The units were removed at intervals and subjected to full production test regimen over temperature from -40C to +85C to insure that the units were still within specifications.

Both styles of PCB-mounted transceivers, (ARINC 801 4-fiber and GC 2-fiber types) were subjected to operational vibration testing to a level of 54 Grms, with spectrum as indicated in Figure 13. The duration was 2 hours per axis, with data running and errors being monitored at 5 Gbps. No errors were detected.

This was followed by 650 G, 0.9 ms shock pulses, 10 shocks per direction in all three axes. The units were exposed to these levels while operating and errors were monitored at 5 Gbps. No errors were detected during any of these exposures.

Finally, the Size #8 contacts were tested for resistance to radiation exposure to 165 krad of gamma radiation from a cobalt-60 source, and 2.5 x 10^{12} neutrons/cm^2, while operating under continuous error monitoring, with no errors detected.

Future test plans include charged-particle testing with protons and heavy ions, and will be reported in future publications.

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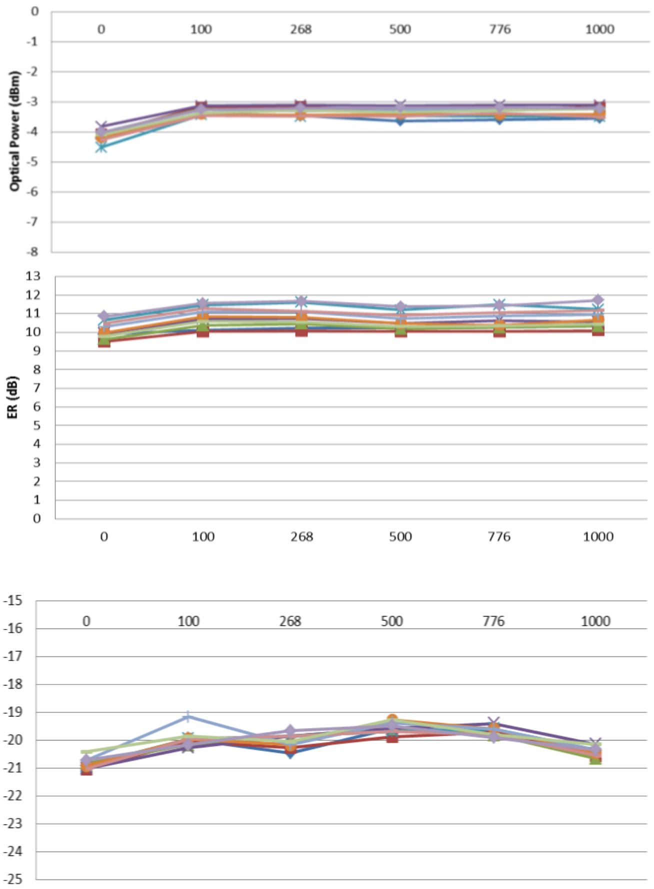

Figure 13. Thermal cycling test from -55C to +125C for Glenair PCB-mount transmitter output power and extinction ratio and receiver sensitivity at 4.25 Gbps. The units were removed from the test chamber at the intervals indicated.

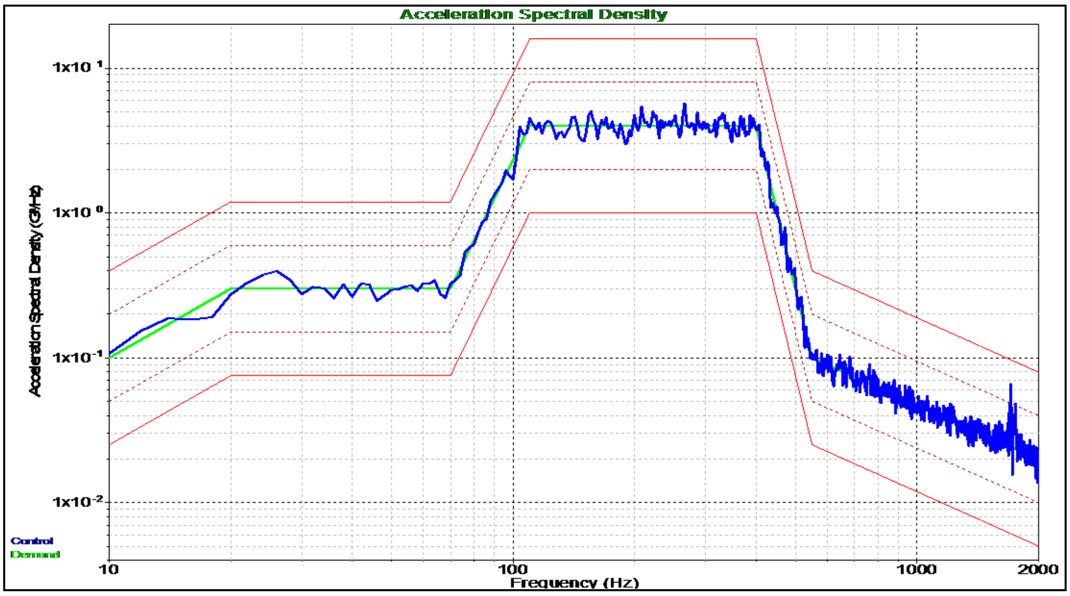

Figure 14. Random vibration profile for 54 Grms operating tests.

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4. Conclusions

Compact, rugged, opto-electronic transmitters, receivers, and transceiver modules in various form-factors were developed and tested to 5 Gbps data rates during various harsh environmental exposures. These transceivers were designed to interface with aerospace-grade fiber-optic connectors suitable for space-flight applications. These devices were subjected to various tests, including thermal cycling, high vibration and shock, and gamma and neutron radiation, and found to survive with no data errors. Further testing is planned.

Acknowledgement

Glenair thanks Technical University Munich for the gamma and neutron radiation testing performed on Glenair products.

References

[1] ESA SpaceFibre draft standard, first issue, 2017.
[2] R.T. Logan Jr., Sean Zargari, Mehrdad Ghara, Huan Do, US Patent 9,297, 972, “Advance fiber-optic contact and method,” issued 29 March 2016.