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PHOTONIC TRANSCEIVERS FOR SPACECRAFT DATALINKS UP TO 5 GBPS

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I. 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. Optical fiber is an ideal medium for high-speed signal transmission on space platforms, since optical fiber cables support data rates up to many tens of gigabits per second (Gbps), are much lighter and smaller than copper wiring of equivalent bandwidth, are immune to radio-frequency (RF) interference from adjacent cables, and therefore require no RF shielding.

However, the availability of suitable photonic transceiver components for space applications is not yet 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 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 briefly review 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.

II. BACKGROUND

We first briefly review the basic design elements 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 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, trans-impedance amplifier IC, and limiting amplifier IC. The trans-impedance 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 5 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.

III. 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 Fig. 1, 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 Fig. 2), 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 [1].

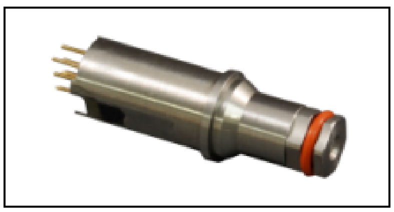

Fig. 1. Opto-Electronic Contact.

Fig. 2. Size #8 contacts in panel-mount avionics connectors: D-sub (upper) and D38999 (lower).

Fig. 3. PCB-mountable quad-output transmitter unit: Top view (upper) and bottom view (lower).

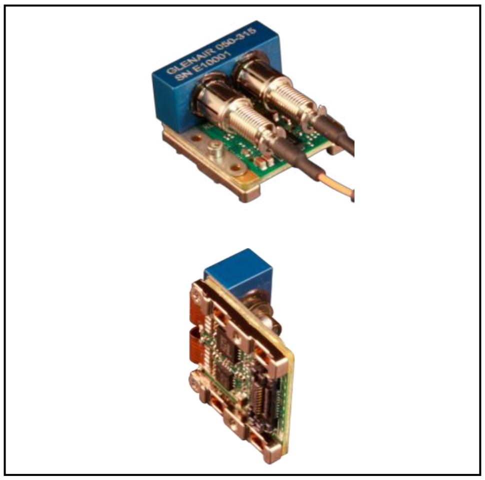

Fig. 4. Two-fiber PCB-mount transceiver form-factor. Top view (upper) and bottom view (lower.)

Fig. 5. Size comparison of Glenair 2-fiber transceiver with commercial datacom SFP pluggable transceiver.

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.

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 Figs. 3 and 4. 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 Fig. 3 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 Fig. 4 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 Fig. 5.

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.

IV. TEST RESULTS

Various reliability and qualification tests were conducted on the parts described above. The filtered transmitter eye diagram at 4.25 Gbps for the Size #8 contacts at various temperatures is shown in Fig. 6, 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.

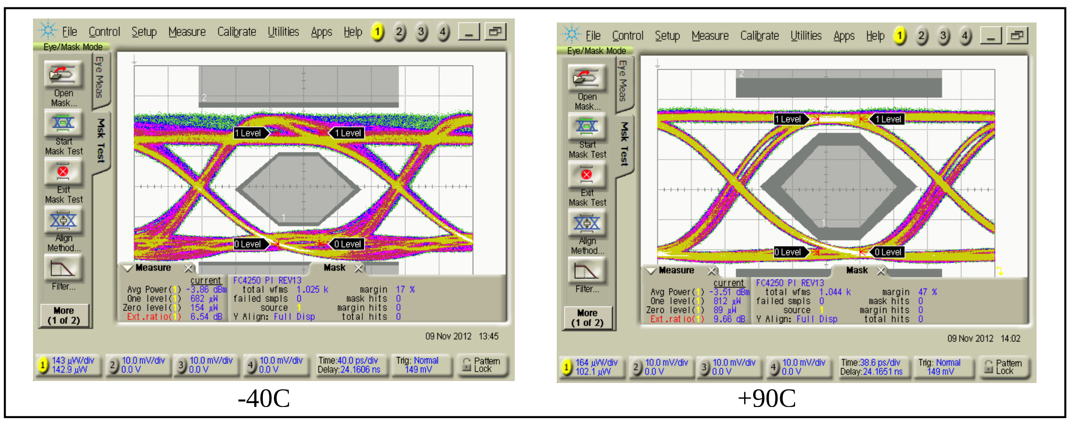

Fig. 6. Size #8 contact filtered eye diagrams at 4.25Gbps.

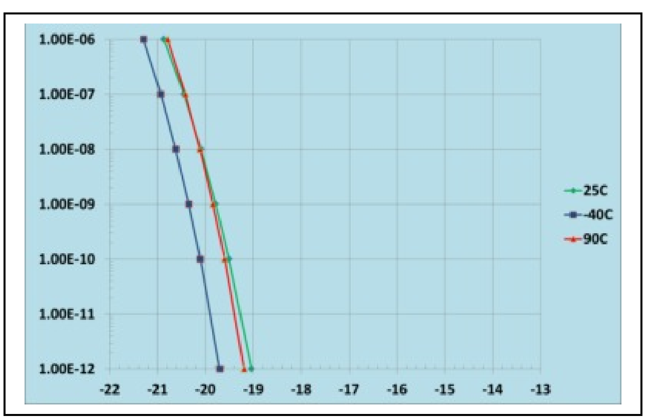

Fig. 7. Receiver sensitivity at 4.25Gbps.

The receiver sensitivity typical for the Size #8 opto-electronic contact measured at 4.25 Gbps at various temperatures is shown in Fig. 7. As evident in Fig. 7, the receiver sensitivity is approximately -19 dBm, which is 5 dB of margin beyond the 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.

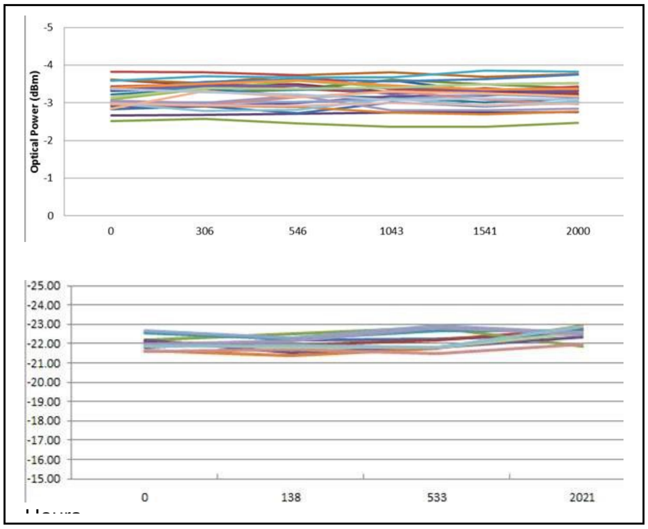

Fig. 8. Accelerated aging of Size #8 opto-electronic contacts. Transmitter output power (top) and receiver sensitivity at 1.25 Gbps (bottom).

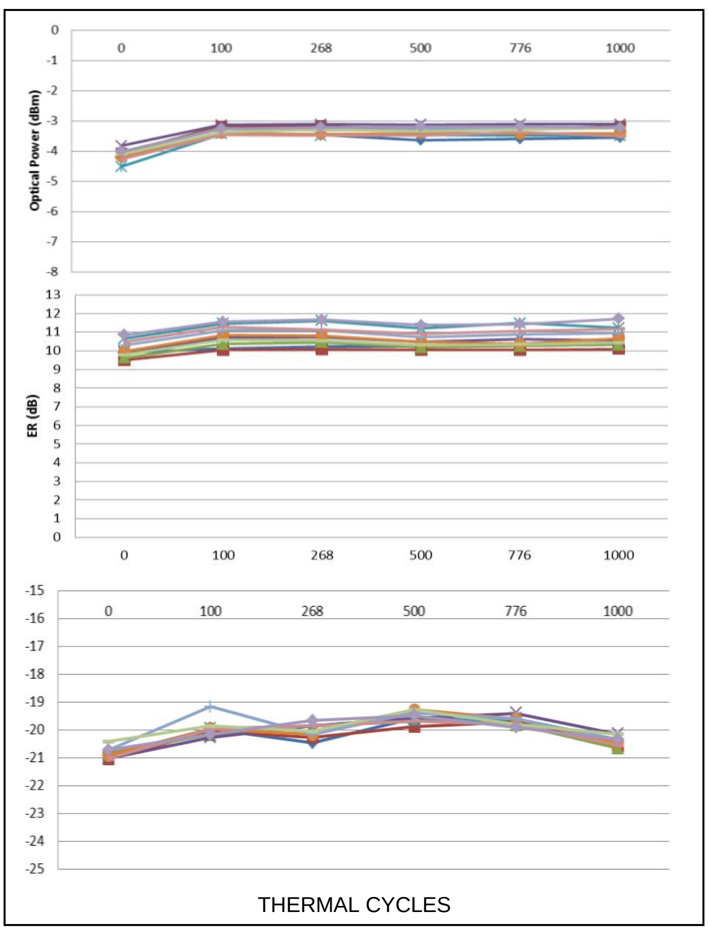

Fig. 9. Thermal cycling test from -55C to +125C for Glenair PCB-mount transmitter output power and extinction ratio and receiver sensitivity at 4.25 Gbps.

Accelerated aging tests were performed on 20 transmitter and receiver devices while operating at +85C, and the results are shown in Fig. 8. No failures were observed. Temperature cycling testing was performed for 1000 cycles from -55C to +125C, non-operating, on the PCB-mount transceivers and the Size #8 contacts with results as shown in Fig. 9. The units were removed at the intervals indicated by data points in Fig. 9 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 Fig. 10. 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.

Fig. 10. Random vibration profile for 54 Grms operating tests.

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.

V. 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.

Acknowledgment
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References

[1] US Patent 9,297,972 Ronald T. Logan Jr., Sean Zargari, Mehrdad Ghara, Huan Do, "Advanced fiber-optic contact and method," issued 3/29/2016.