

High density optical fiber interconnect for photonic data processing architectures

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ABSTRACT

Optical and photonic networks are essential to next-generation spacecraft as missions demand higher throughput, greater flexibility, and software-defined functionality. A major obstacle is the ability to manage, route, and scale hundreds to thousands of optical fibers within the limited mass and volume available on space platforms. Here we report on a novel multichannel fiberoptic interconnect for space applications that alleviates critical issues associated with effective connectivity across photonic payloads: channel density, space-grade robustness, and ease of integration. The device is an optomechanical interconnect module consisting of a rectangular housing that accommodates four MT-format ferrules. The four rectangular MT-ferrules are arranged vertically parallel in a horizontally aligned row with uniform spacing supported by an insert inside each of the two mating connector bodies.

Optical engagement between the mating interconnects is established via a mechanical lever actuator. Actuating the lever applies a controlled, uniform linear force that (1) translates one ferrule array toward the other, (2) ensures precise axial alignment of mating MT-ferrules, and (3) provides the required mating pressure for low-loss physical contact without transferring substantial force to the payload panel.

The rectangular form factor of the interconnect module allows dense packing of multiple interconnects on a payload panel. This provides exceptional channel densities when compared to circular connectors. The tool-free latching mechanism simplifies the practical installation and reduces process documentation efforts.

The proposed design and its benefits are underpinned with FEM simulations and the results of a space application environmental testing campaign. Initial thermal cycling and random vibration testing confirm the simulations: no phenomena compromising space application are observed. The findings motivate further product design based on the initial results.

Keywords: Photonic payloads; fiberoptic interconnects; high-density optical interconnects; MT ferrule; tool-free optical connectors; FEM simulations;

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1. INTRODUCTION

Photonics is penetrating all applications in spaceflight including satellite platforms, payloads and launchers. This trend is exacerbated by digital payloads in high- and very-high throughput telecommunication satellites that process ever higher data rates, from 28 Gb/s today poised for 56 Gb/s and even 112 Gb/s [1]. The base componentry to realize photonic payloads and networks include optical transceivers, modulators, photodiodes, optocouplers, optical fibers and fiberoptic connectors.

Despite the more recent surge in space photonics that is driven by the decline in launch costs and the concomitant technoeconomic viability of versatile satellite constellations, the need for multifiber connectors has been present for over two decades. Initially triggered by implementation of fiberoptic data links in instrumentation for scientific space missions, most prominently the broad deployment of fiberoptics on the ISS, the theme now has become pressing broadly across all sectors of spaceflight. Following pioneering work by the Ott group [2][3] on applying MT ferrules, by 2021 circular connector solutions for 8×MT12 and 10×MT12 around the Q-MT Titan portfolio of Radiall were qualified [4] and first deployed on SES-17. Further circular MT-based connector solutions considered for space are available from Glenair [5] and Amphenol [6]. Currently, efforts to standardize high-density multifiber connectivity are ongoing at ESA by extending ESCC3420 [7] and formulating a new generic specification document jointly with end-users and manufacturers.

Initially motivated by the need to simplify AIT of large optical fiber shuffles for photonic payloads, the authors embarked on the development of a novel multifiber connector. Key objectives are to achieve easy, tool-free integration and high packing density of multiple adjacent connectors, while maintaining high channel counts and space-grade robustness.

2. DESIGN

The interconnect module is developed to enable a high-density optical interface while maintaining mechanical robustness and suitability for harsh operating environments. The resulting design (see Figure 1) features a slender rectangular cross-section accommodating four MT ferrules and, in principle, up to 128 optical fibers within a compact envelope. This geometry provides a favorable compromise between optical channel density and structural rigidity. Furthermore, the rectangular outer profile enables multiple connector modules to be arranged directly adjacent to one another, thereby maximizing packaging efficiency while minimizing the required installation volume. The selected architecture is therefore particularly suitable for applications in which available space and mass are limited.

A key design objective is to minimize the number of individual components without compromising functionality. Reducing the part count simplifies manufacturing and assembly processes, decreases the number of potential failure sources, and improves overall system reliability. This aspect is particularly relevant for aerospace applications, where maintenance and repair after installation are generally not possible. The proposed design consists only of components required for optical alignment, contact force generation, structural load transfer, and mechanism operation, thereby reducing assembly complexity and manufacturing effort (see Figure 2).

The locking concept is designed to require access from only one side of the connector. A lever-actuated locking mechanism enables tool-free mating and de-mating while maintaining unrestricted accessibility in densely packed assemblies. Unlike circular fastening concepts that require lateral access from multiple sides, the chosen solution allows multiple interconnect modules to be positioned directly adjacent to each other without compromising operability. As a result, connector spacing is governed primarily by external housing dimensions rather than assembly or maintenance requirements.

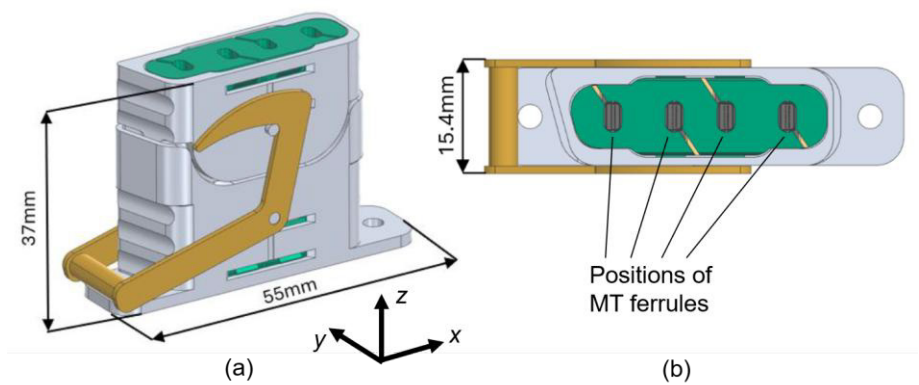


Figure 1. CAD modeling of the interconnect module housing four fiber optic MT-style ferrules. (a) 3D view with definition of coordinate system xyz ; (b) top view.

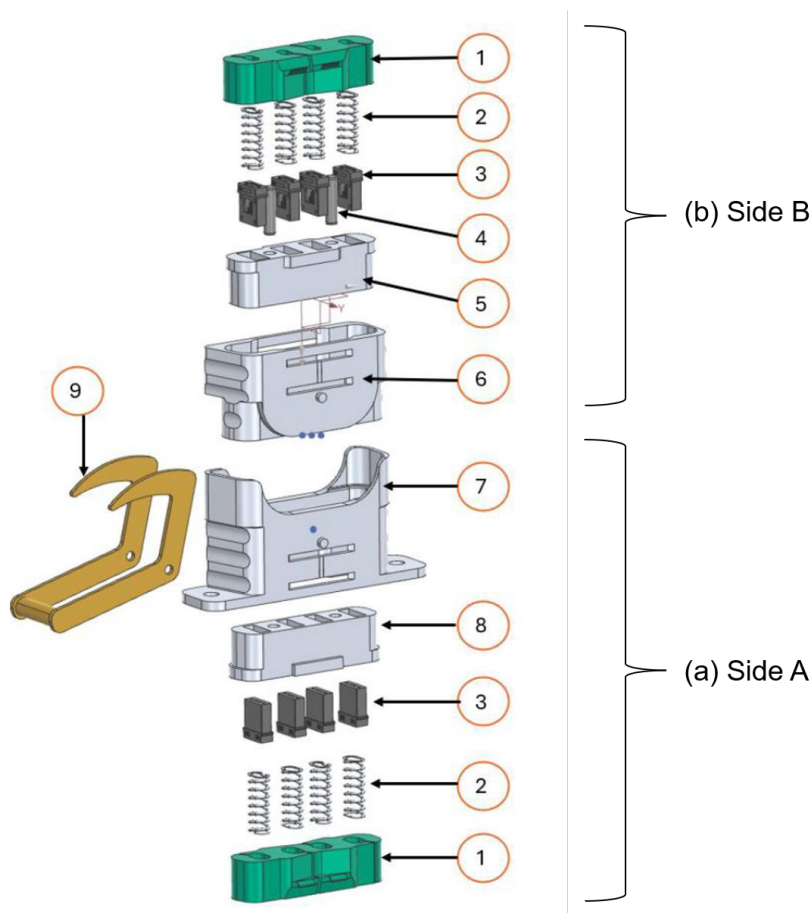


Figure 2. Exploded view of the interconnect module. (a) Side A (in this version designed as flat-mountable receptacle and accommodating the locking mechanism); (b) Side B (plugs into side A). Description of the individual parts of the interconnect module can be found in Table 1; pins of the MT ferrules are omitted.

Table 1. Description of the individual parts of the interconnect module, as shown in Figure 2.

Item no. in Figure 2	Designation	Quantity in side A	Quantity in side B	Material
1	Spring retainer	1	1	Aluminium alloy EN AW-7075-T6
2	Spring	4	4	Stainless steel 1.4310 (AISI 301)
3	Ferrule	4	4	Glass-filled polyphenylene sulfide (PPS) thermoplastic
4	Down pin	0	2	Stainless steel AISI 420
5	Male ferrule holder	0	1	Aluminium alloy EN AW-7075-T6
6	Male housing	0	1	Aluminium alloy EN AW-7075-T6
7	Female housing	1	0	Aluminium alloy EN AW-7075-T6
8	Female ferrule holder	1	0	Aluminium alloy EN AW-7075-T6
9	Locking lever	1	0	Aluminium alloy EN AW-7075-T6

Mechanical guiding concept

Accurate alignment of the optical interfaces is essential because even small positional deviations between mating fibers can increase insertion loss and reduce transmission quality. To achieve sufficient positional accuracy, a three-stage guiding concept is implemented.

The first guiding stage is provided by the outer contours of the male and female housing components. These features establish the coarse alignment of both connector sides during the mating process and ensure that the assemblies are positioned correctly before any precision-guiding elements engage. The second guiding stage is realized by two dedicated alignment pins integrated into the connector structure. These pins precisely position the ferrule holders relative to each other and reduce translational and rotational degrees of freedom between the connector sides. By implementing the majority of the alignment functionality into the housing structure, unwanted loads are prevented from being transferred to the high-precision and vulnerable ferrule interface. The third and most precise guiding stage is provided by the guide-pin system integrated into the MT ferrules. These alignment pins establish the final ferrule positioning and ensure accurate fiber-to-fiber alignment down to the micrometer level. As a result, ferrule-level alignment is decoupled from the primary structural alignment functions of the connector housing, improving robustness and reducing the risk of performance degradation resulting from manufacturing tolerances or mechanical loads.

In addition to the hierarchical alignment concept, the connector features an increased guiding length between the mating sides, improving angular alignment by reducing the influence of dimensional tolerances and assembly inaccuracies.

Material selection

The material selection is based on the requirements of low mass, high specific strength, dimensional stability, and compatibility with environmental conditions. The primary structural components, including the housing, ferrule holders, spring retainers, and locking lever, are manufactured from EN AW-7075-T6 aluminium alloy. This material offers an excellent strength-to-weight ratio and provides sufficient mechanical strength while reducing the overall system mass compared with steel-based alternatives. Furthermore, the selected alloy demonstrates good machinability and is widely used in aerospace structures.

3. FINITE ELEMENT ANALYSES

Finite element analyses are performed to evaluate the mechanical and functional integrity of the interconnect module under relevant load cases for space applications. The analyses focus on thermo-mechanical deformation, preservation of ferrule preload and the dynamic behavior of the ferrule-spring unit under vibrations. Since optical performance depends

on stable physical contact and maintained precise alignment of the fiber cores, the simulations are used to assess whether structural deformation or vibration-induced dynamic mass forces can affect the ferrule contact condition.

Thermo-mechanical analysis

Any deformation of the housing elements influence the effective spring compression and, thus, also the ferrule contact force. Since signal performance depends on appropriate contact force between the mating ferrules, force deviations due to thermal expansion must be limited. Although simulation results reveal thermal expansions of the module's structure in the sub-mm range at a temperature of + 85°C (see Figure 3 and Figure 4), the resulting spring force is only reduced by 0.001 %, indicating that the ferrule contact condition remains unaffected.

Figure 4

The proposed architecture is closely linked to the objective of minimizing the total number of components. To reduce mass, manufacturing effort, and assembly complexity, the guiding and alignment functionality is not decoupled from the module's outer housing structure. Instead, the ferrule holders and alignment features are integrated directly into the structural housing components (see Figure 2). As a result, the three-stage guiding chain, as described in Section 2, becomes directly coupled to thermally induced housing deformations. To avoid any relative displacements of the housing structure being transferred to the ferrule support system and ultimately to the optical interface itself, proper tolerancing was applied to ensure the decoupling of the ferrule's guide-pin alignment from thermal displacements of the housing.

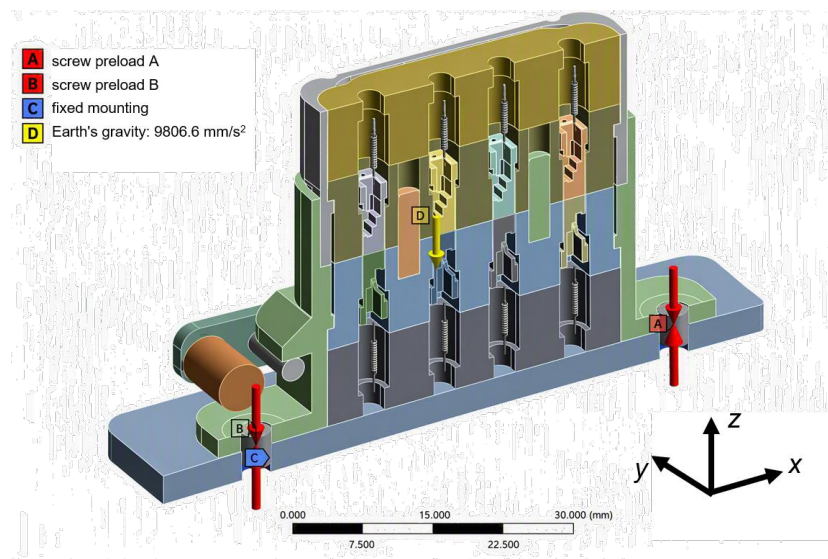


Figure 3. Boundary conditions of the interconnection module for the thermos-mechanical analysis: Connector Side A fixed at the lashes (marker A, B and C); gravity (marker D) acting in direction of the negative z-axis.

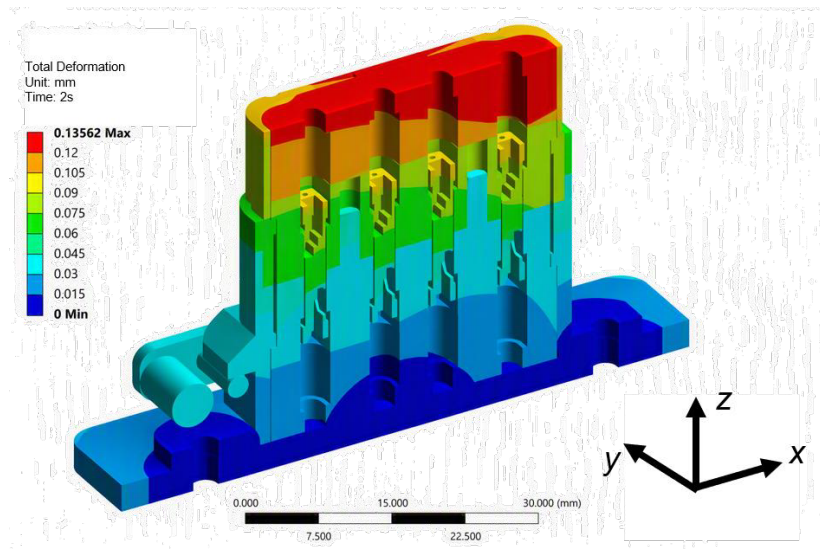


Figure 4. Deformation analysis of the interconnect module at a temperature of +85 °C.

Modal analysis

To evaluate the behavior of the optical contact interface under vibration exposure , a simplified finite element model is used, where a mated ferrule pair is represented as a spring-mass system (see Figure 5). This simplification allows efficient investigation of the relative motion between the ferrules while preserving the governing contact mechanics.

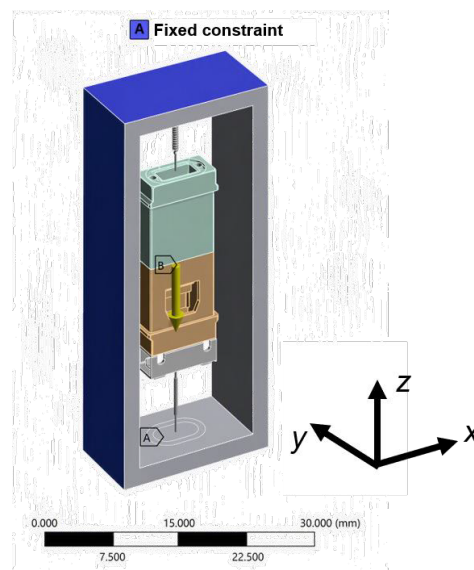


Figure 5. Simplified subassembly model including the applied boundary conditions for the investigation of the dynamic displacement behaviour of the ferrules under vibration exposure along the z -axis; fixed constraint at support structure (marker A) and gravity (marker D) acting in direction of the negative z -axis.

The analysis focuses exclusively on excitation along the connector axis (z -direction). This direction is considered the most critical because it coincides with the spring preload force and the ferrule mating motion. In the mated connector state, the ferrule pair behaves as a free-floating subsystem constrained primarily by the preload springs. Consequently,

vibration-induced separation can only occur through relative displacement in the preload direction. This assumption allows the dynamic investigation to be reduced to a one-dimensional problem.

Dynamic simulations are performed using the acceleration spectral density (ASD) profile defined according to the environmental test requirements of ESCC Basic Specification No. 2263420 [8] and the random vibration test methodology according to IEC 60068-2-64 [9]. The primary evaluation criterion is the variation of the spring preload forces during excitation. A significant reduction of the spring force would indicate a loss of contact pressure and potential lift-off of the ferrule interface. Conversely, constant spring forces imply preservation of the contact condition between the mating ferrules.

The simulation results show only minor fluctuations of the spring forces throughout the excitation period, with a maximum relative preload force reduction of approximately 0.15 % to 9.4 N. The maximum displacement of the axial position of the ferrule pair is approximately 15 μm , which remains negligible compared to the total spring preload displacement of 1.05 mm. As a result, the preload force is almost completely preserved and, hence, it can be concluded that the optical contact condition remains functional and that no insertion loss increase due to contact separation is expected. Random vibration testing presented in Section 5, confirms these conclusions.

4. TEST SAMPLE CHARACTERISTICS

The environmental testing presented in this work aims to prove the feasibility of the interconnect module for space applications. Therefore, the testing is based on the evaluation test program defined in the ESCC Basic Specification No. 2263420 [8] and consists of a temperature cycling test and a random vibration test.

As device under test (DUT) for environmental testing, a prototype of the interconnect module according to the mechanical design described in Section 2 was machined and assembled. Figure 6 shows the assembled module in both unmated and mated states. In addition, Table 2 summarizes the material details of the applied fiber optic termination. The suitability of the used MT ferrule type of manufacturer US Conec for space flight environments was already investigated by Ott et al. [2]. Fiber termination is done using standard epoxy adhesive (between fiber and ferrule).

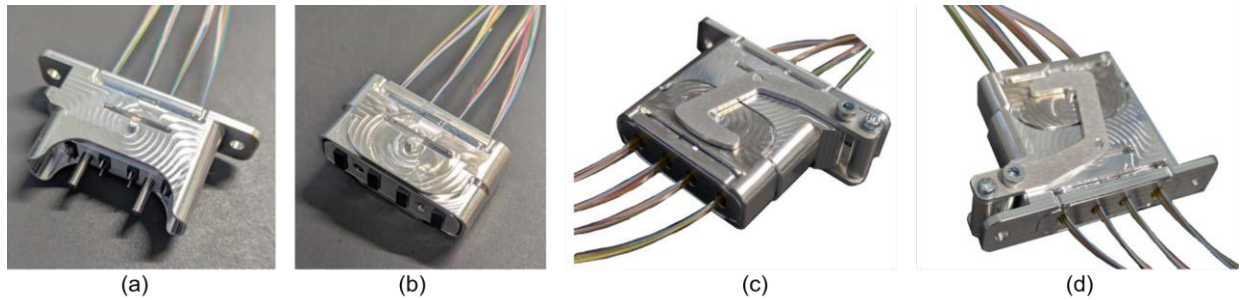


Figure 6. Machined and assembled prototype of the proposed investigated module. (a) Side A; (b) Side B; mated and locked (c, d) interconnect module.

Table 2. Materials of the fiber optic termination.

MT ferrule type	12 fiber MT ferrule (Manufacturer: US Conec)
Fiber type	Bending insensitive single-mode fiber according to ITU-T G.657.A2 (acrylate coating, outer diameter of 250 μm)
Adhesive type between fiber and ferrule	EPO-TEK® 353ND

During testing, the optical signal attenuation of three out of the twelve fiber channels per MT ferrule are monitored. To guarantee traceability, Figure 7 defines a coherent nomenclature for numbering the fiber channels of the module under test. Accordingly, the first, sixth and twelfth channel of each of the four ferrules are monitored during testing, i.e., a total of twelve monitored fiber channels.

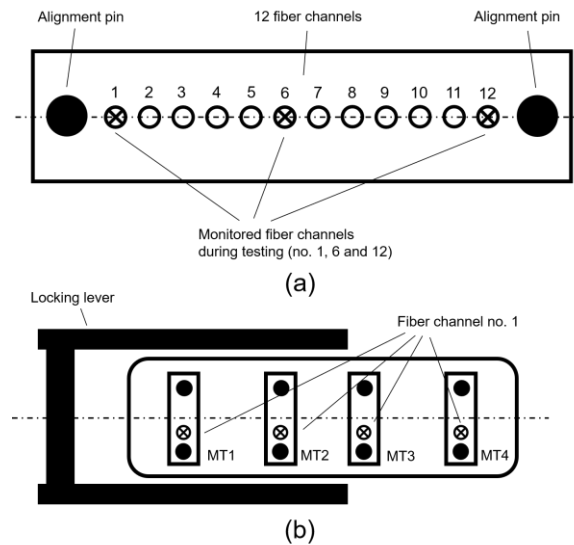


Figure 7. Nomenclature and monitored fiber channels: (a) Front view of a single MT ferrule terminated with 12 single-mode fibers, channels 1, 6 and 12 are monitored during testing; (b) top view of side A of the interconnect module with designations of the individual MT ferrules (MT1 to MT4) and orientation of respective fiber channels; the nomenclature “MT1-1” refers to fiber channel no. 1 of ferrule MT1.

5. RANDOM VIBRATION TESTING

To prove the vibration resistance of the proposed interconnect module and especially the vibration dependency of the optical signal attenuation, a random vibration test is performed along all three perpendicular main axes (x , y , z) in addition to the temperature cycling. shows the shaker test equipment and the mounting arrangements for the respective coordinate axis (orientation of coordinate system is consistent with Figure 1). For fastening the module to the shaker structure, the lashes on module Side A and two screws tightened with controlled torque are used (see also Figure 2).

The parameters of the ASD profile are chosen according to the environmental test definitions in ESCC Basic Specification No. 2263420 [8] and the testing itself is carried out in accordance with IEC 60068-2-64 [9]. Figure 9 depicts the ASD profile and Table 3 defines the parameters of the vibration testing. Accordingly, the module was exposed to the ASD profile three times consecutively for each axis orientation. The module remained connected for the test series and after each vibration run a visual inspection from the outside was done.

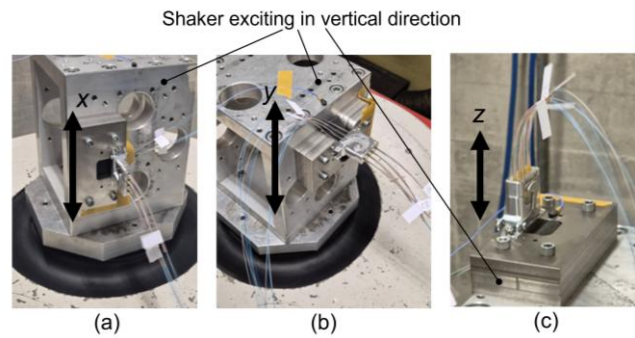


Figure 8. Random vibration testing setup: Shaker (exciting in vertical direction) with mounted interconnect module. (a), (b) and (c): Mounting situations with x-, y- and z-axis of the interconnect module aligned with shaker axis, respectively.

Table 3. Parameters of the random vibration test.

Parameter	Value
Frequency $f_{1 \text{ start}}$ [Hz]	20
Frequency $f_{1 \text{ start at ASD max}}$ [Hz]	100
Frequency $f_{2 \text{ end at ASD max}}$ [Hz]	300
Frequency $f_{2 \text{ end}}$ [Hz]	2000
ASD level [g^2/Hz]	2.2
ASD acceleration [dB/Octave]	+3
ASD deceleration [dB/Octave]	-5
Acceleration level RMS [m/s^2]	35g
Crest factor (ratio of peak to RMS value)	2.5
Number of measured perpendicular axes	3
Duration of test per axis [min]	7.5
Measurement light wavelength [nm]	1550
Sampling frequency of optical attenuation [Hz]	4000
Ambient conditions: Temperature [$^{\circ}\text{C}$]	24 ± 2
Ambient conditions: Relative humidity [%]	55

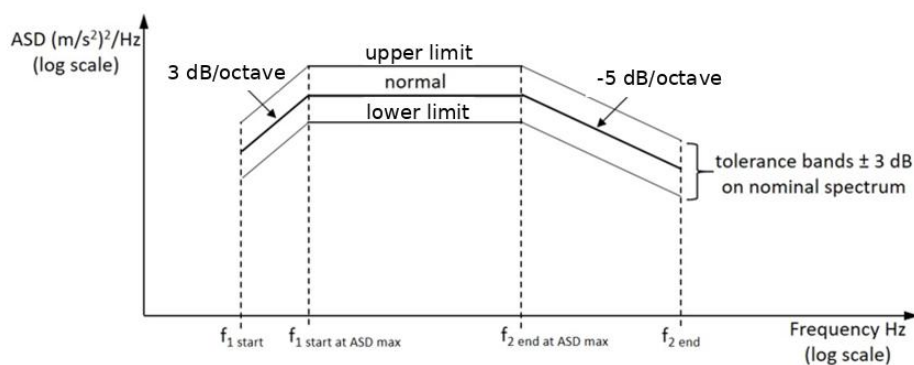


Figure 9. Acceleration Spectral Density (ASD) as a function of the vibration test's frequency spectrum (values according to Table 3).

The measured changes of optical signal attenuation along the x -, y - and z -axis are shown in Figure 10, Figure 11 and Figure 12, respectively. All channels along all three axes experience transient attenuation changes that stay within a range of ± 0.15 dB. The observed attenuation changes of ± 0.15 dB cannot solely be attributed to the interconnect module itself. The abrupt and creeping signal steps occurring in some of the data channels along the y - and z -axis stem from relaxation effects of the relatively long-length optical fibers as they settle in place after movements of the shaker are initiated during testing. Such effects are not observed for the x -axis run because fiber routing is much more favorable compared to the arrangements for y - and z -axis testing (see Figure 8). After such a signal step, typically, the signal remains at an offset value and continues oscillating around a steady value.

The vibration exposure along the axis of the preloaded ferrule springs (z -axis) is viewed as the critical direction since dynamic mass forces directly influence the physical contact conditions at the touching areas of the connected fiber cores. The data along the z -axis (Figure 12) does not indicate that the contact condition of the fiber cores is significantly affected by dynamic forces, in which case substantial transient signal behavior would have been observed.

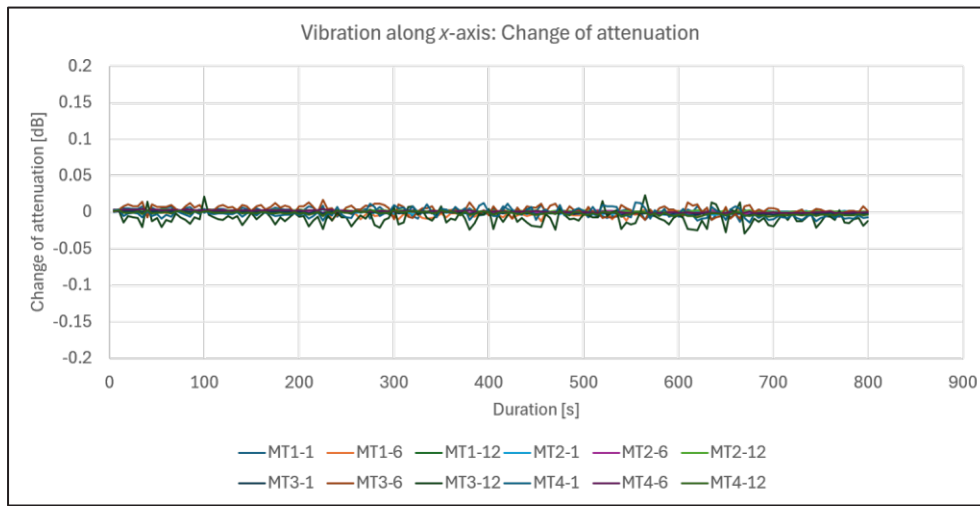


Figure 10. Random vibration testing, excitation along interconnect module's x -axis: Change of attenuation of the twelve monitored fiber channels over test duration; positive values correspond to a loss increase.

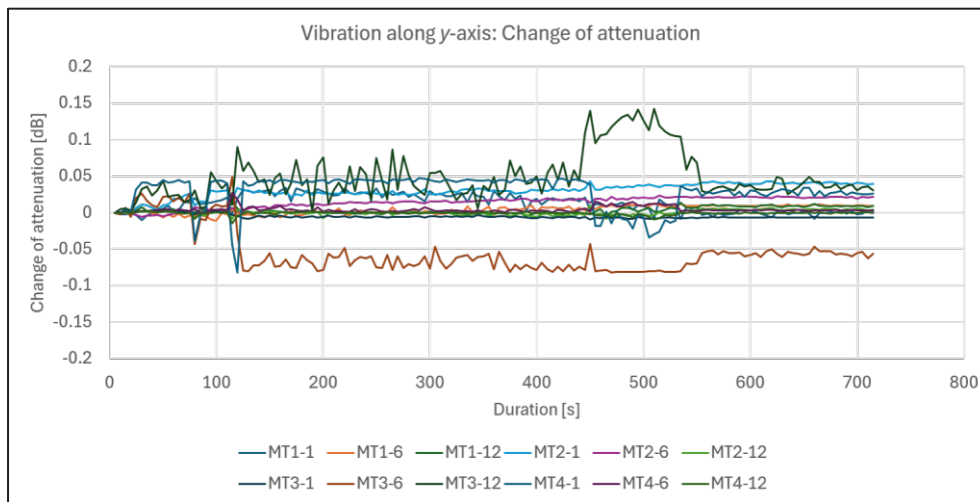


Figure 11. Random vibration testing, excitation along interconnect module's y -axis: Change of attenuation of the twelve monitored fiber channels over test duration; positive values correspond to a loss increase.

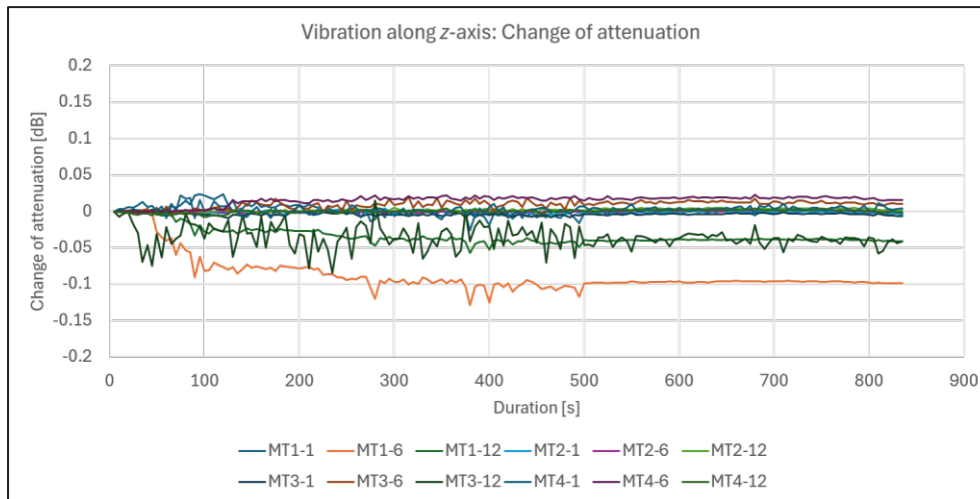


Figure 12. Random vibration testing, excitation along interconnect module's z-axis: Change of attenuation of the twelve monitored fiber channels over test duration; positive values correspond to a loss increase.

Following the vibration test runs the interconnect module was demounted and analyzed regarding damage and wear. Whereas no permanent damage of the polished ferrule surfaces is detected, the aluminium parts of the housing structure show clearly visible signs of mechanical wear (see Figure 13). The dark abrasion marks, indicated in Figure 13 at several locations, imply that the individual parts of the housing structure move relative to each other during the vibration exposure.

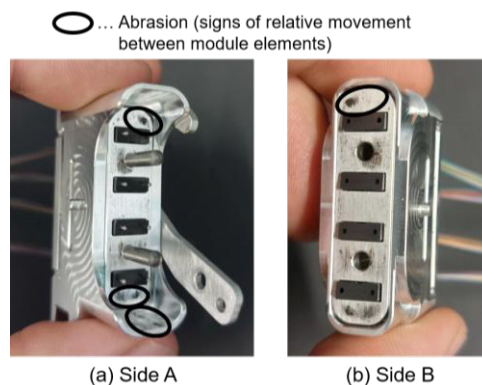


Figure 13. Pictures showing abrasion at the contact surfaces of the mechanical elements between Side A (a) and Side B (b) of the interconnect module.

6. TEMPERATURE CYCLING TESTING

For temperature cycling, the DUT (mated interconnect module) is placed in a temperature chamber, whereas the fibers are guided to the chamber's outside through a feedthrough and connected to a signal analyzer (see Figure 14). Pluggable connections between the DUT and the signal analyzer are placed outside the chamber and related signal attenuations are compensated for in the results. As defined in [8], the temperature cycling is tested in accordance with

IEC 61300-2-22 [10] and follows the severity category “Extreme environment”, defining the temperature range spanning $-40\text{ }^{\circ}\text{C}$ to $+85\text{ }^{\circ}\text{C}$. The complete set of testing parameters is summarized in Table 4.

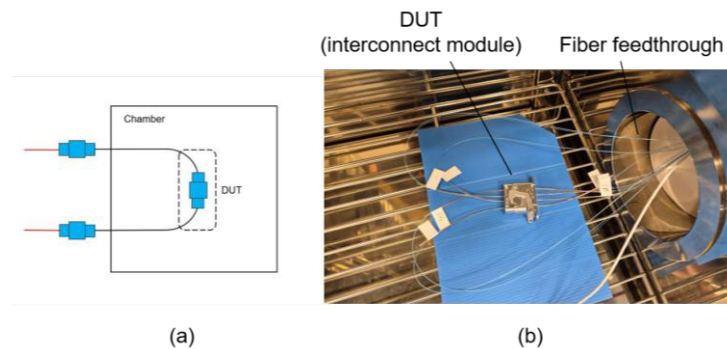


Figure 14. Setup for temperature cycling testing. (a) Schematic overview with DUT (interconnect module) placed inside the temperature chamber; (b) inside view of the temperature chamber with optical fibers guided outside via a feedthrough.

Table 4. Parameters of temperature cycling testing (in accordance with IEC 61300-2-22, Table 1, severity category E (Extreme environment)).

Parameter	Value
Low temperature [$^{\circ}\text{C}$]	-40
High temperature [$^{\circ}\text{C}$]	+85
Dwell time at low and high temperature [min]	60
Temperature change rate [K/min]	1
Number of cycles	12
Starting temperature [$^{\circ}$]	Room temperature ($\approx 25\text{ }^{\circ}\text{C}$)
First temperature after start	Low temperature
Cable length inside temperature chamber [m]	0.5 ± 0.1
Measurement light wavelength [nm]	1310 and 1550
Measurement sampling interval [s]	300 (1/300 Hz)

Figure 15 and Figure 16 show the change of optical signal attenuation over the testing duration measured at a wavelength of 1310 nm and 1550 nm, respectively. Each of the monitored fiber channels is plotted separately. During preparation of the test setup and handling of the DUT the fiber of channel MT3-6 broke. As a result, this channel is missing in the data visualizations.

In general, the channels of the tested module show similar behavior for both wavelengths. The anomaly observable for channel MT3-1 both at 1310 nm and 1550 nm is likely to originate from a particle (dirt or dust) on the ferrule endface reducing the signal transmission. This assumption is supported by the fact that the affected channel shows an even larger signal loss at 1310 nm compared to the longer wavelength of 1550 nm, which can be explained by the smaller mode field diameter (MFD) at 1310 nm. The larger ratio between the obscured mode area due to a particle and the MFD leading to higher signal losses is frequently experienced when characterizing fiber optic interconnects.

For the remaining channels, except for channel MT3-1, the behavior of the changes of attenuation during the temperature cycling testing must be differentiated. Whereas, the variations of attenuation stay well within the range of $\pm 0.2\text{ dB}$ at the measurement wavelength of 1310 nm, the values measured at 1550 nm vary slightly more. Usually, this is a sign for a fiber stress point somewhere along the measured fiber length. Because the field of the bigger MFD at 1550 nm extends further into the fiber cladding, signal losses are more sensitive to mechanical forces acting onto the fiber and resulting in stress that impairs the confinement. Apart from this, once the system has settled after the first temperature cycle, all channels (except MT3-1) show a recurring behavior along the remaining eleven temperature cycles, which validates the suitability of the interconnect module’s mechanical design for the tested temperature range.

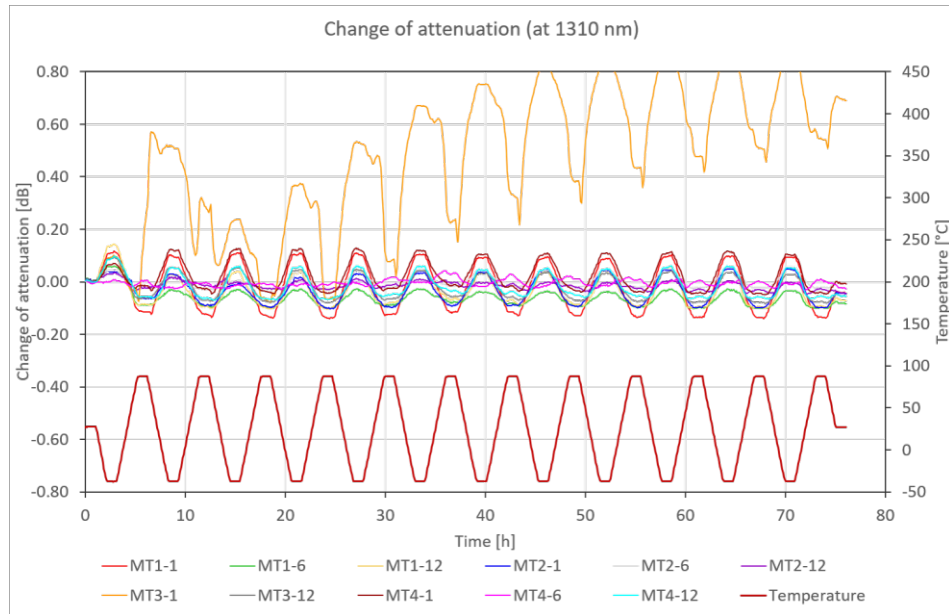


Figure 15. Temperature cycling test: Change of optical attenuation at a wavelength of 1310 nm; positive values correspond to a loss increase (nomenclature according to Figure 7).

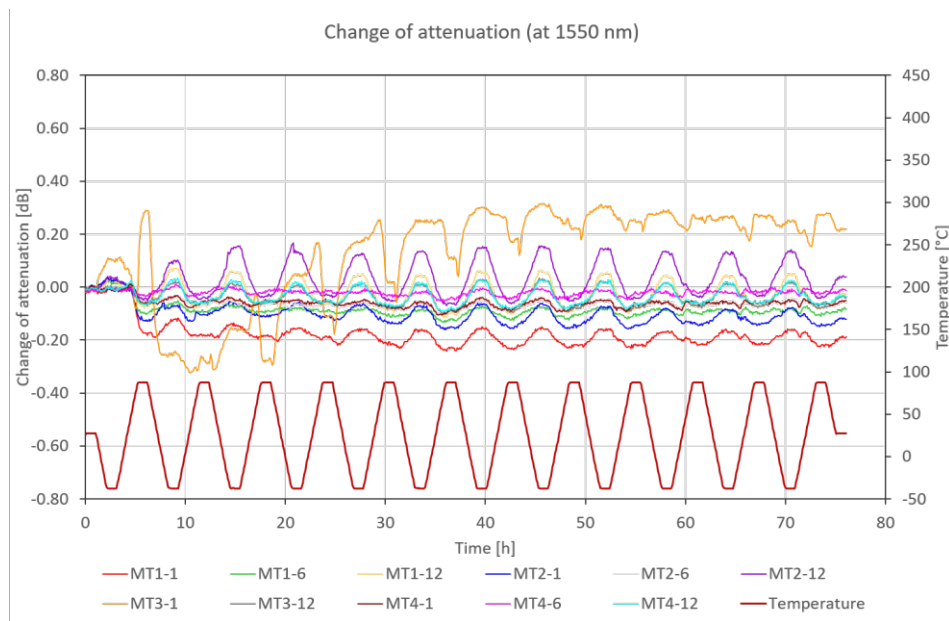


Figure 16. Temperature cycling test: Change of optical attenuation at a wavelength of 1550 nm; positive values correspond to a loss increase (nomenclature according to Figure 7).

7. CONCLUSIONS

A novel multichannel fiberoptic interconnect for space applications was developed and evaluated through numerical simulations and environmental testing. The design combines four MT ferrules within a compact rectangular housing and incorporates a tool-free locking mechanism, enabling high channel density and simplified integration. Finite element analyses predict that thermal loads and vibration exposure have only a negligible influence on optical contact conditions. These findings are confirmed experimentally. During random vibration testing, attenuation variations remain within approximately ± 0.15 dB, and no evidence of vibration-induced loss of physical contact is observed. Repeated temperature cycling from -40 °C to $+85$ °C likewise demonstrates stable and repeatable optical performance. Strong correlation between simulation and test results validates the mechanical design approach and confirms that the optical interface remains functional under representative spaceflight environments. Post-test inspection reveals no damage to the MT ferrule endfaces, although wear marks are observable on several aluminium housing contact surfaces. While these effects do not measurably impact optical performance, they indicate opportunities for improving long-term vibration robustness. The feasibility of the proposed interconnect concept has therefore been demonstrated.

Future developments will focus on reducing module height and mass, optimizing the locking mechanism, addressing channel count scalability, introducing a dedicated housing seal, improving protection of the fiber transition, and further enhancing vibration resistance. In addition, air-gap ferrule concepts may be considered. With these refinements, the presented architecture offers a promising solution for next-generation high-density photonic payload connectivity.

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