Performance Methodologies of a Modular Miniature Photonic Turn Connector

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ABSTRACT

Next generation parallel optical interconnects that incorporate monolithic collimating lens arrays require new procedures and guidelines for performance certification and visual inspection. This paper, after reviewing design specifications, will report performance methodologies for a modular miniature photonic turn connector that is used as an interface into VCSEL and photodiode arrays. A new insertion loss test procedure is introduced that can be used to screen connector performance without the need for vendor-specific optical engines. Data will be presented to show how induced defects affect the connector performance and thus establish inspection criteria. Finally, recommended cleaning procedures will be addressed.

Keywords: Fiber optic connector, lens array, parallel optics, collimating beam, visual inspection, insertion loss, cleaning

1. INTRODUCTION

Next generation computing, switching, and routing systems will soon require Tb/s level interconnections between active devices. Transmission speeds continue to increase to efficiently accommodate drivers such as the growth in rich content, virtualization, and multi-core processing. The IEEE 802.3 Ethernet Working Group has attempted to predict future bandwidth growth rates for networking aggregation and computing applications [1]. The demand projection paths, shown in Figure 1, predict that 10 Gb/s Ethernet will shortly become commonplace at the network edge, and 40 Gb/s Ethernet at the network aggregation layer.

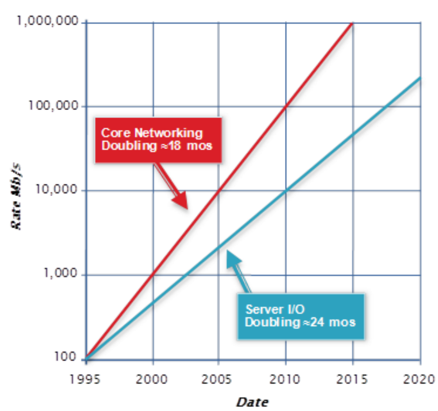


Figure 1. IEEE 802.3 Ethernet Working Group predicted bandwidth demand growth rates [1].

Data center network cores, inter-switch links, inter-building and inter-campus connections for enterprise network will likely require 100 Gb/s [2]. If current trends continue, there will be an increase in network traffic of a factor of 10 by 2015, as compared to 2010, and by a factor of 100 by 2020 [1].

Traditional serial communication strategies cannot support the growing transmission demands. New technologies take advantage of parallel communication standards, which produce higher data rates through simultaneous transmit and receive capabilities. Thus, parallel interfaces, either electrical or optical, provide a reliable path to achieve these next generation interconnects. However, purely transitioning to parallel interfaces will not provide sufficient bandwidth using conventional copper solutions [3]. As data rates move beyond 10 Gb/s, optical technologies offer distinct advantages over copper in terms of density, power, weight, thermal management, and link length. Parallel optics solutions are currently being implemented in place of electrical devices for both on-card and card edge transmission systems. Vertical cavity surface emitting laser (VCSEL) arrays, widely available in embedded formats, allow transmit and receive interfaces to be located on-card, close to the main ASICs. By embedding and optimizing the VCSEL engines on card, copper traces can be minimized, which leads directly to higher transmission rates, improved EMI containment, reduced heat generation, and simplified thermal management [4].

Historically, embedded optical module form factors conform to SNAP12 and POP4 standards. Fiber optic connections are then used to transport the signals to and from the embedded modules. High density MPO connector based jumpers are typically used to interface into the embedded module and carry the signal to the card edge [3]. The bandwidth density obtained by aggregating multiple embedded modules at the card edge via the MPO connectors eclipses the density obtained by edge mounted pluggable modules or active-optical cables (AOCs).

1.1 Traditional Multi-fiber Connectors

The most common multi-fiber connector, the MPO, was originally developed by NTT Laboratories for use in subscriber network lines in an outside plant environment. The connector has matured over the past twenty years, and fiber is now secured to the ferrules with standard optical connector grade thermal cure epoxy and polished with commercially available connector polishing machines. In order to obtain stable, low insertion-loss performance, the fiber tips of the mated pairs must come into physical contact with each other. This physical contact requires tightly controlled termination, polishing and metrology procedures; these attributes are the main cost drivers of traditional multi-fiber interconnects. In addition to maintaining physical contact, each fiber tip in the ferrule must be kept relatively free of defects and debris to ensure the signal is not attenuated [5]. Figure 2 illustrates the primary attributes impacting the performance of traditional MPO connectors: component precision, polished endface geometry, fiber tip quality and cleanliness [6].

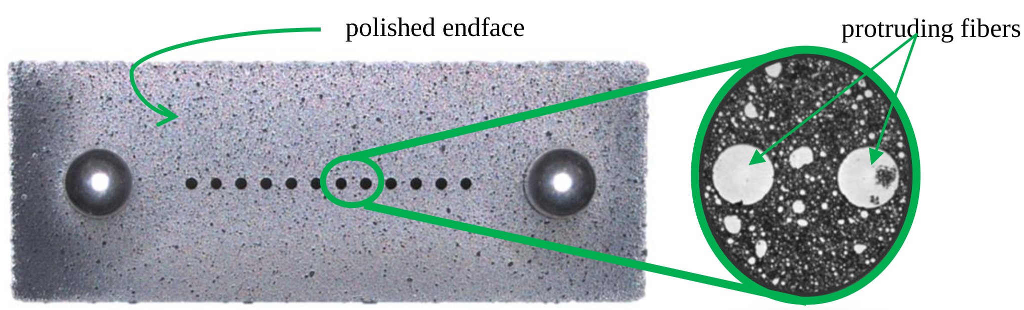


Figure 2. The end-face of a typical male MPO based multi-fiber ferrule. The quality of the end face, which includes the geometry and cleanliness of the polymer substrate and the protruding glass fibers impact the performance of the ferrule during physical contact. These requirements are greatly relaxed in lens based ferrules.

1.2 Next Generation Optical Interconnects

The growing bandwidth requirements discussed above demand high-speed optical solutions with reduced form factors, cost, and module-coupled insertion losses. The newest miniature parallel optic modules offer a path to integrate higher I/O densities directly into board designs. Modules are now available in footprints as small as 8.2 mm X 7.8 mm [4]. Fiber optic connectors need equally innovative solutions to simplify the coupling between the modules and the fiber connectors, as well as improved performance. A miniature multi-fiber connector has been developed and released to address the connector needs [7]. The connector is a monolithic connector that incorporates a collimating lens array to condition and direct the parallel beams, and to act as a seamless pluggable interface into these miniature parallel optic modules. The lensed connector provides low cost termination via the implementation of laser cleaved fibers, as well as the complete elimination of exposed fiber endface, mechanical polishing and traditional interferometry. The elimination of a polished fiber array greatly reduces the cost and complexity associated with physical contact based multi-fiber interconnects. However, next generation parallel optical interconnect components that incorporate lensed connectors require new procedures and guidelines for performance certification and visual inspection. As the new connector deviates from the traditional MPO inspection and testing paradigms by eliminating the exposed fiber, considerable engineering work has been put into developing new methodologies that are predictive of the final connector/module performance. After presenting the initial design specifications and implementation, the performance methodologies for the connector will be discussed.

2. PHOTONIC TURN CONNECTOR

The photonic turn connector consists of two major components, the ferrule and connector hardware, as shown in Figure 3. The molded ferrule (Figure 3a) is a monolithic component that contains the primary precision components of the lens array, microholes to capture the fibers, and mating surfaces for the module. A connector housing, shown in Figure 3b, snaps on to the ferrule to seal and protect the lens array while simultaneously providing the latching interface that facilitates perpendicular mating to the module. Multiple housings are available to provide features such as increased cable strain-relief or reduced form-factors, and will be discussed in detail below. Finally, in order to mate the ferrule to the VCSEL or photodiode array, an interface is needed. The interface is available either as a stand-alone OEM mechanical-optical interface (MOI), as in Figure 3c, or already integrated into commercially available module [8].

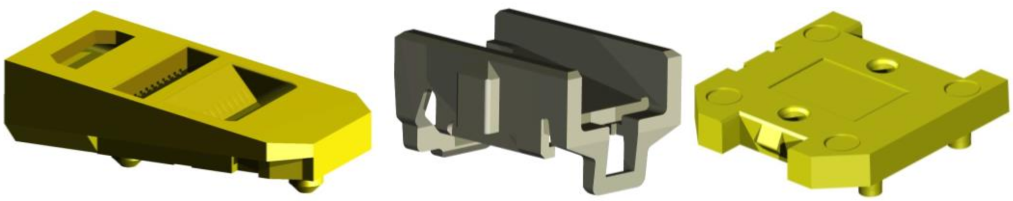


Figure 3. 3a) The bare monolithic multi-fiber ferrule prior to fiber installation. 3b) Typical connector housing for protecting ferrule lens array and providing latching features, prior to installation. 3c) Stand-alone mechanical-optical interface for mating between ferrule and VCSELs.

2.1 Monolithic Ferrule

The key features of the ferrule are illustrated in Figure 4. An array of microholes that capture and position the optical fibers are aligned to both the lens locations and the alignment posts located on the bottom of the part. The fiber stop plane, located in front of the microholes, acts as a stop for the fiber array. The combination of these features ensures that the fibers are repeatably and reliably located in the ferrule. In addition, use of the microholes and a permanent stop plane simplifies fiber termination procedures and eliminates all of the conventional connector polishing and interferometry requirements. Using a laser cleaver, standard multimode ribbon fiber is stripped and subsequently cleaved 2.75 mm beyond the end of the ribbon matrix. While traditional mechanical cleavers can be used, use of a laser cleaving process is recommended due to the resulting rounded fiber tips and clean endface along with a highly controlled cleave length [9]. As compared to the fiber tips generated with a mechanical cleave, the rounded fiber tips reduce the amount of debris generated, due to friction, during fiber insertion. The cleaved fiber array is then inserted into the ferrule microholes. An index matched epoxy is then inserted into both epoxy openings, and the fiber is pushed into its final resting place against the stop plane. Inserting the epoxy first ensures that the index-matching epoxy coats the fiber endfaces and eliminates air pockets between the fibers and the stop plane. The assembly is then cured and the connector housing snapped into place. The entire cleave and termination, and cure process can easily be completed, on average, in less than 2 minutes, greatly reducing the time involved in standard fiber termination and polishing. The index-matched epoxy can be either a visible-cure epoxy to expedite cure times, or a traditional fiber optic thermal cure epoxy. Specific epoxy performance results will be discussed further below.

The array of aspheric, asymmetric lenses relies on total-internal reflection (TIR) to redirect the light path from the optical fiber, down and perpendicular to the connector mating plane. The lens prescription was simultaneously optimized for both transmit and receive communications. The ferrule accepts a collimated beam from the VCSEL module and the lens condenses the light for efficient fiber coupling. Use of collimated light entering and exiting the ferrule reduces the alignment tolerance requirements and the effects of debris on the optical exit window. An optically smooth exit window is molded into the bottom of the ferrule between the alignment posts to allow the light to enter and exit the ferrule with minimal distortion. The two openings towards the rear of the ferrule are for index-matching epoxy to securely bond the fiber array in place.

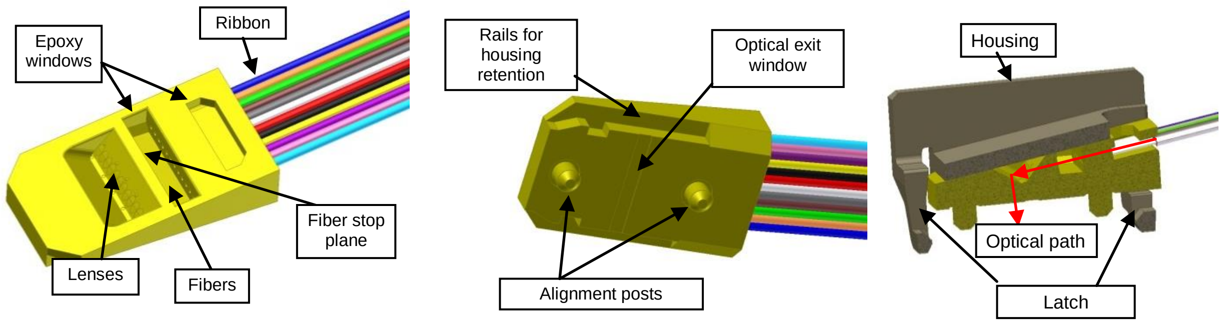


Figure 4. a) Top of ferrule, b) bottom of ferrule, and c) ferrule with housing installed.

2.2 Connector Housing

The connector housing has been designed to protect the lenses while providing a consistent and repeatable mating interface to the module. Several different housings have been designed for a variety of applications. All of the housings work with the same ferrule and share the same latch design. The housing, shown in Figure 5, provides the initial rough alignment and holds the assembled connector in place, while allowing the ferrule to float laterally. This float permits the precision alignment posts and transceiver alignment holes to control the optical path alignment without over-constraining the connection.

Figure 5. 5a) The standard connector housing protects the lens array while providing latching features to connect to the VCSEL interface. 5b) Round cable version of the housing provides improved strain relief while adding an outer housing to help seal the VCSEL module against outside contamination. 5c) Reduced height connector housing for low-overhead applications.

2.3 Mechanical-Optical Interface

A passive, mechanical optical interface (MOI) has been developed that couples the connector system to the embedded active optics on the board. As with the ferrule, the MOI, shown in Figure 6, is a monolithic molded component. The MOI has two alignment holes that accept the matching pins from the ferrule, and two latches that mate to the connector housing. The combination of the holes and latches create a pluggable interface such that the connector can be attached or removed from the board for testing and cleaning, or cable routing purposes, and reliably reconnected for repeatable performance. The MOI has an array of lenses that provides direct coupling between the active board-level optics and the modular connector, and provides a common platform for the connector seating, regardless of vendor specific active optics. The MOI is mounted above the VCSEL or photo-diode array and the MOI lens array actively aligned. As with the ferrule lens array, the MOI has been designed to allow efficient coupling in either transmit or receive condition directly between the active optics of the board and the module connector.

The optics of the MOI are collimating lenses that relay light between the VCSEL array on the circuit board and the photonic connector. In a transmit configuration, the output from each VCSEL transmitter is collimated by the MOI so that it is focused by the photonic connector lens for coupling into attached multimode fiber. Theoretical modeling, using conventional VCSEL designs, predicts a coupling efficiency of 76% when used in the transmit configuration. In a receive configuration the nearly collimated output from the ferrule is focused by the secondary optic onto the detector, and slightly higher coupling efficiencies are expected, depending on the detector specifics.

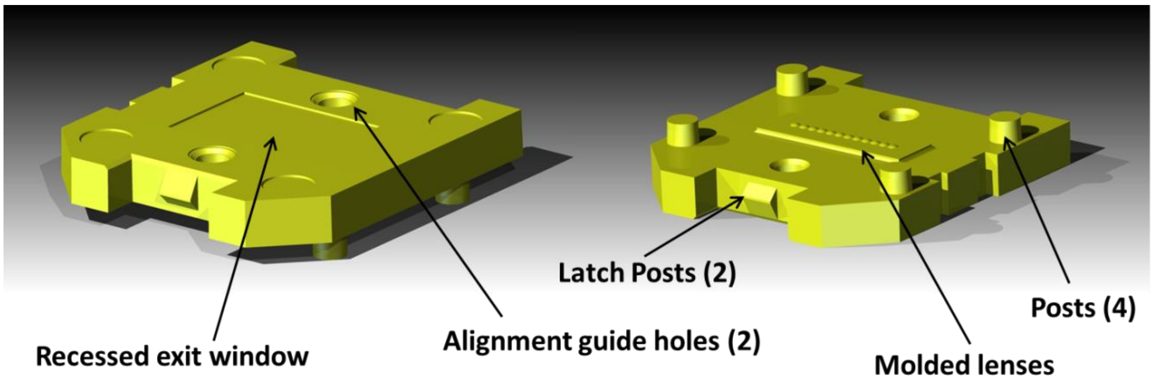


Figure 6. MOI interface for mating between the VCSEL array and the modular connector. The main components are shown in a) the top and b) the bottom of the component.

3. PERFORMANCE TESTING

The performance of the connector system is judged on its ability to couple power between the module and the fiber bi-directionally. To minimize the need for application specific module based test stations, a common test platform has been developed for the connector, based on a combination of multi-fiber connector insertion-loss testing and connector/module power coupling performance [4]. Moreover, to minimize the need for new equipment and training, the new insertion loss test method, called the Interposer Test, utilizes traditional loss testing technology used by cable manufacturers [10] [11], consisting of a multi-fiber launch cable and wide area detector.

The Interposer Test, depicted in Figure 7, uses an Interposer fixture that mates two opposing connector assemblies. Light is launched from the reference ferrule assembly and coupled into the device under test (DUT) ferrule assembly, creating a path through which performance can be measured.

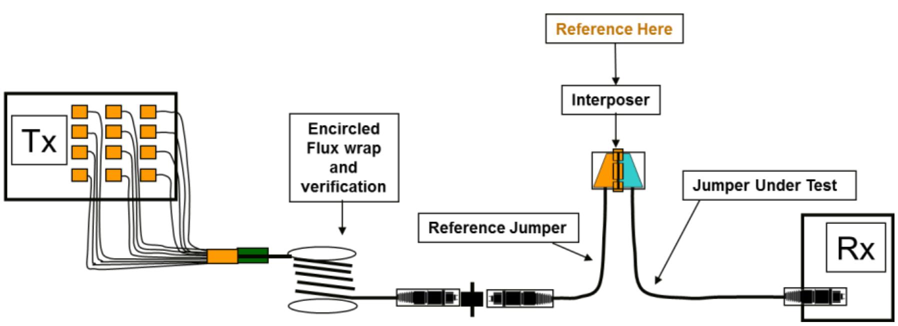


Figure 7. Setup for Interposer insertion loss testing.

The reference ferrule assembly is connected to the test equipment launch jumper, which is encircled-flux compliant [12]. The reference jumper, a higher quality jumper that is similar in concept to the master launch jumpers used in standard fiber optic test systems, is measured to reference the system prior to testing. The DUT assembly is mounted to the Interposer and the transmitted power is recorded as the Interposer loss in dB. Extensive testing correlating module and photonic turn connector performance led to a benchmark target of 2.0 dB as a relative loss value to judge the connector performance.

4. VISUAL INSPECTION

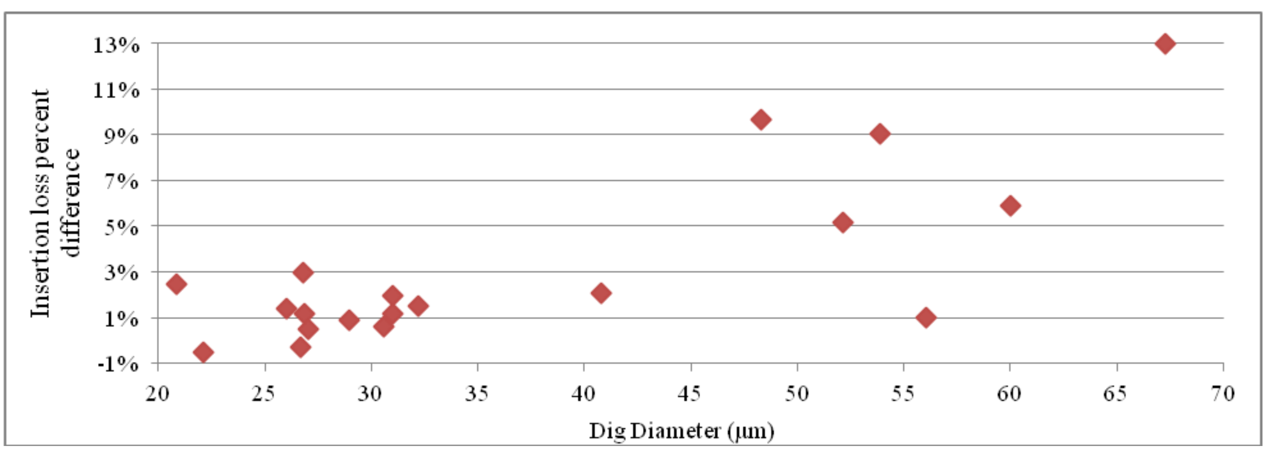
After reducing termination costs and eliminating polishing and interferometry steps, another major advantage of the photonic turn connector is insensitivity to debris or scratches. The collimated light that exits the connector has a substantially larger spot than traditional fiber optic connectors. Standard multi-mode fiber has a 50 µm core diameter, large exit angle, and a cross-sectional area of 1,963 μm^2. The photonic turn ferrule has a 180 µm collimated beam output diameter, with a subsequent cross-sectional area of 25,446 μm^2. With an area almost 13X larger, the connector system is significantly less sensitive to debris or scratches. Therefore, a relaxed visual inspection criteria, relative to traditional fiber end-face requirements, has been developed.

4.1 Methodology

The primary area of concern for visual inspection during final quality inspection in a production environment is the exit window of the connector, as shown in Figure 4b. Using conventional optical scratch/dig definitions [13] and the Interposer Test, experiments were conducted to determine the change in loss as a function of dig diameter and scratch width. In each case, the exit window was sub-divided into twelve independent 180 µm diameter areas, through which the light from each channel was passing. This treatment of the channels individually is similar to current multi-fiber visual inspection techniques and will simplify automated inspection processing at a later point. Connectors were characterized both before and after either scratches or digs were deliberately induced in each spot sub-division. In the case of digs, the damage was located in the center of each sub-division, which represents the worst case impact on insertion loss performance. Individual scratches of various widths were also placed across the center of the exit window, and always crossed the full length of the lens spot; the following results are scratch length independent as a worst case length is assumed, and the criteria is based purely on the scratch width.

4.2 Results

Figure 8a below, shows the change in Interposer loss versus dig diameter; diameters above 40 µm demonstrate a steep increase in Interposer loss, while below 40 µm the change in loss is insignificant. Individual scratches below 14 µm wide do not significantly impact device performance, while scratches above 14 µm wide are unacceptable. Additional testing on 141 channels showed that multiple small scratches (less than 5 µm wide) had no impact on Interposer loss. When comparing the data sets of the minor scratched parts and unaltered parts, both sets had an average final Interposer loss of 1.4 dB and identical coefficients of variation. Furthermore, t-tests showed that there was no difference in the population sets at the 1% significance level. In other words, multiple scratches of less than 5 µm wide on the exit window have no effect on connector performance.



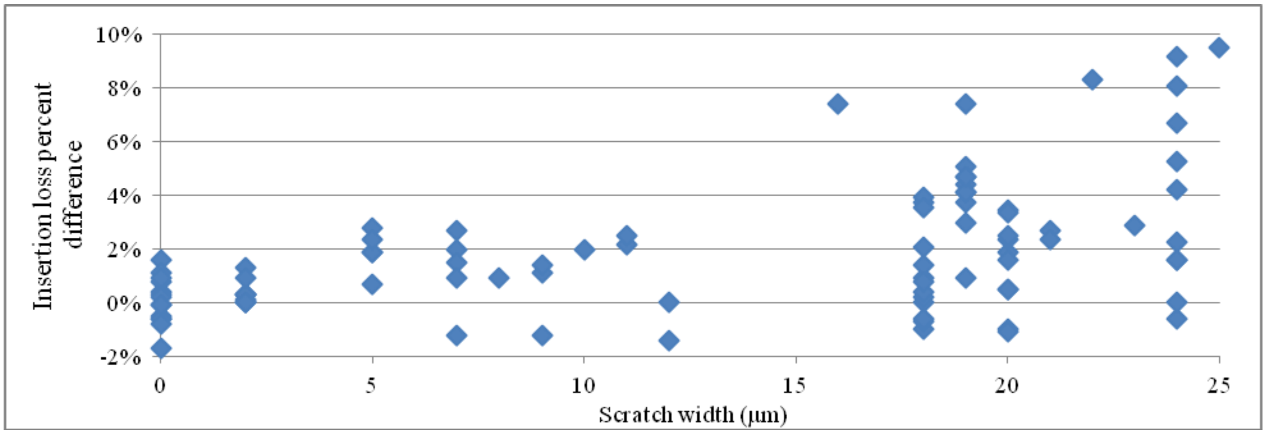


Figure 8. 8a) Diameter of deliberate dig damage and the effect on Interposer insertion loss. 8b) Similar measurements for Interposer insertion loss versus scratches on the connector exit window.

5. CLEANING

Even though the lensed connector is less sensitive to debris, scratches and digs, cleaning is still occasionally necessary to remove contaminants. A dry cleaning method is generally preferred over wet cleaning, as residual impurities left from the wet cleaning agent could potentially impact the refractive index of the exit window. Therefore, a low pressure cleaning mechanism, coupled with a soft, high-density fabric mesh was developed. In order to reduce the possibility of introducing scratches while removing debris, a micro-fiber fabric is used in conjunction with a spring loaded saddle in the ferrule seating area. The tool was tested against various contaminants; Figure 9 shows a typical image of a connector exit window before contamination, post contamination and post cleaning, consecutively.

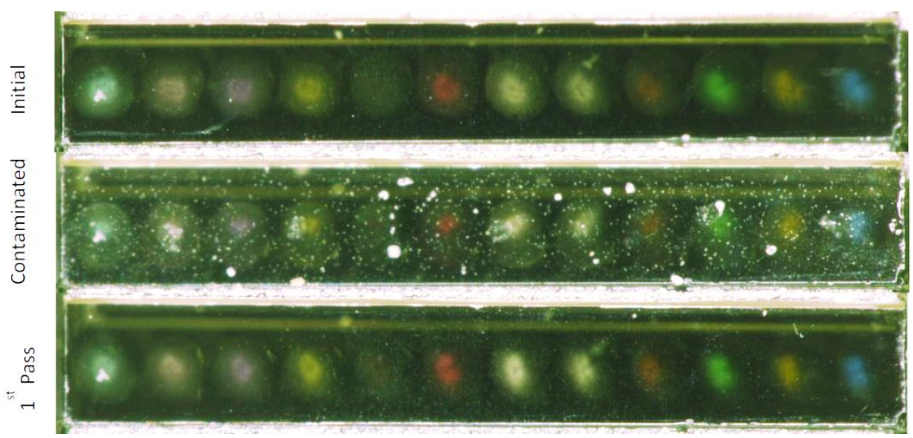


Figure 9. A connector exit window a) initially, b) after deliberate contamination with Arizona road dust, and c) after one pass with the cleaner.

6. ENVIRONMENTAL TESTING

The connector was subjected to industry-standard Telcordia GR-1435-CORE environmental and mechanical testing [14]. As was discussed previously, the ferrule can be terminated with either light-cure or thermal cure epoxies, depending on the specific customer requirements. While light cure epoxies are significantly faster, with cure times of less than two minutes, they are only capable of passing the controlled environmental requirements of the GR-1435 specification. If more extreme environmental requirements are expected at the installation site, several thermal cure epoxies are very capable of withstanding the tougher environments. Three different thermal cure epoxies from two different vendors were tested under GR-1435 conditions and passed the full battery of environmental and mechanical tests. Figure 10a shows the Interposer loss distribution of eight connectors before and after the full GR-1435 uncontrolled environmental and mechanical test regimen. Figure 10b shows the Interposer loss values for all channels after the qualification. All channels remained below a performance target of 2.0 dB Interposer loss [4]. The deviation after each test and deviation from the initial qualification Interposer test values remained below the 1.0 dB delta threshold determined in conjunction with module and system designers. The average Interposer loss initial value was 1.42 dB, while the average final value was 1.41 dB. In addition, the system has been subjected to an array of application specific environmental and mechanical testing, such as an 85°C/85%RH environment for 14 days. Post dry-out measurements showed that no channels deviated from the initial Interposer loss measurements by more than 1.0 dB. Expanded testing has shown no additional performance degradation after three days of 120°C.

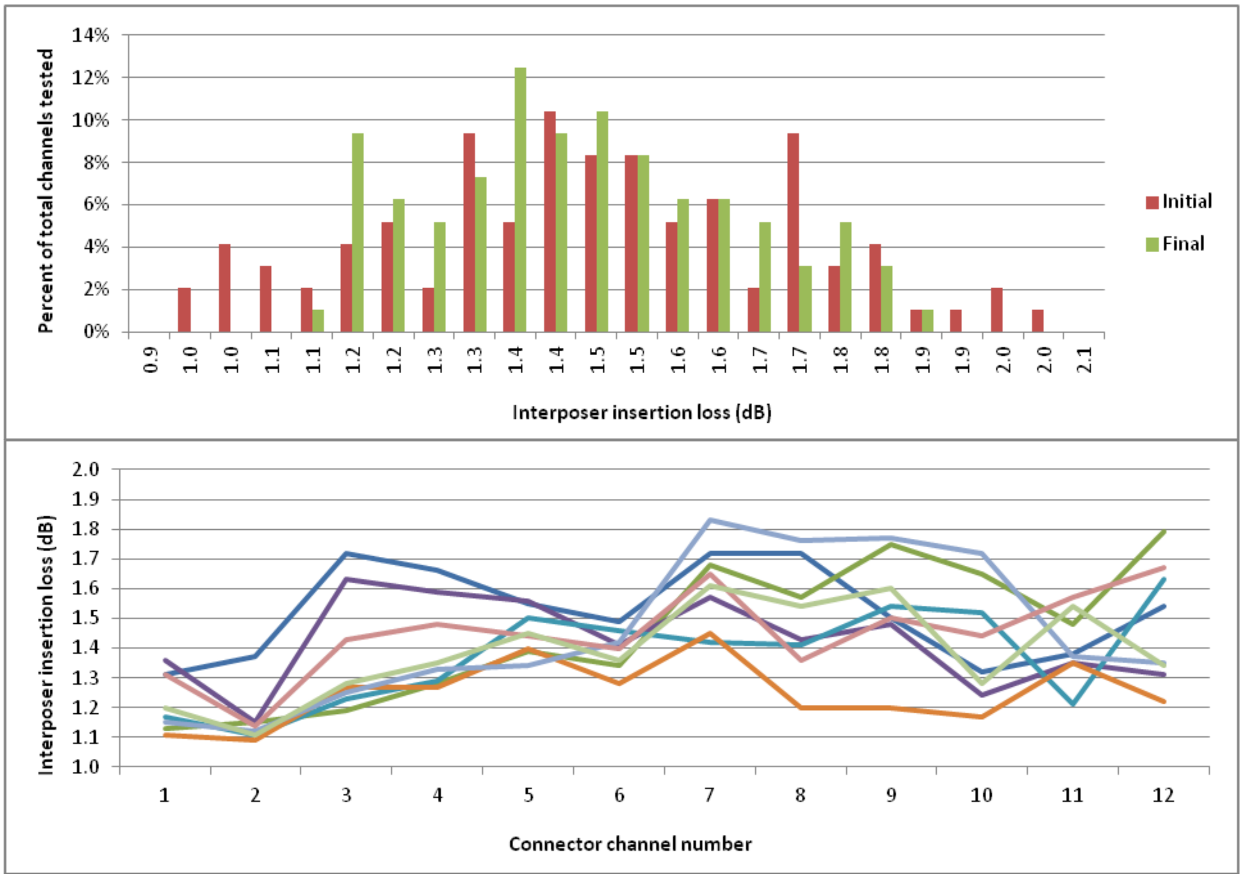


Figure 10. a) Distribution of Interposer loss measurements before and after GR-1435 uncontrolled environmental and mechanical qualification and b) final Interposer loss for all jumpers after completion of the qualification. Pass/fail specifcation for the testing was < 2.0 dB.

7. FUTURE WORK

Photonic connector testing is also underway to determine the feasibility of single-mode operations with the connector. Preliminary testing indicates the connector may be successful in single-mode applications with only minimal modifications.

Anticipated next generation improvements to the MOI may include the implementation of diffractive patterns for launch conditioning and integrated features for power monitoring purposes. Photonic turn connector designs may include multi-row ferrules to facilitate higher density interconnects and optical modules.

8. CONCLUSIONS

A novel miniature detachable photonic turn connector and accompanied module optical interface have been developed to facilitate repeatable perpendicular coupling into board mounted VCSEL and photo-diode module arrays. An Interposer optical test method was developed to certify the performance of the connector. Due to the connectors 180 µm collimated beam output diameter, the performance of connector system is less sensitive to debris or scratches thus a new visual inspection criteria was established.

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