Performance Methodology and Characterization of a Multi-Fiber Expanded Beam Lensed Optical Interconnect

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***Abstract*— The demand for high performance, cost-effective optical interconnects is driving the need for novel connectors in the optical communication industry. A multi-fiber lensed ferrule has been introduced that addresses backplane and ganged application requirements through the use of molded, expanded beam optics. The new ferrule maintains the same footprint as traditional multi-fiber ferrules, but uses an array of lenses on the front face to expand and collimate up to sixty-four channels simultaneously. The monolithic ferrule uses a hermaphroditic post and hole mating system to eliminate the costs associated with traditional steel alignment pins. The final result is a collimated beam connector system that enables debris insensitive connections for standard multi-mode optical fiber.**

The implementation of a new connector system requires the development and verification of an accompanying test infrastructure. Theoretical modeling of both expected insertion loss and back-reflection performance is presented, followed by experimental data to validate the model's assumptions. The elimination of a traditional physical contact connection changes the impact of Fresnel reflections on reference and test setups, and therefore a modification of the conventional loss testing methodology is presented. Furthermore, a study of deliberate connector exposure to oil and debris confirms the connector insensitivity to contamination.

Finally, long-term reliability is established after mated pairs of expanded beam connectors were successfully exposed to a series of environmental and mechanical test sequences; presented data shows an average change of < 0.01 dB after days of thermal aging, humidity exposure, and temperature cycling, along with 1000 consecutive connector matings.

Keywords-optical interconnects; expanded beam; lensed ferrule; optical performance; enviromental testing

I. Introduction

Embedded parallel optic modules address the need for increasing density in optical interconnect technology at the card edge. With current architectures, density is achieved through multi-fiber connectors employing traditional MT ferrules, which require physical contact between the mated pair in order to obtain a low and stable insertion loss. This physical contact requires very tightly controlled termination, polishing and metrology procedures, which drive the cost of traditional multi-fiber deployments.

While traditional, physical contact MT ferrules are suitable for demanding low-loss, high performance applications, they are not optimized for short reach, high-density, cost sensitive applications. For multimode interconnect densities beyond 24 fibers, obtaining and maintaining physical contact of the fiber tips becomes challenging with the state of the art polishing and termination technology. As a result, the mated fiber tip interface of high fiber count MT ferrules becomes unstable, resulting in optical interference and amplified return losses. For fiber counts greater than 12, increased spring force is necessary to achieve physical contact. This higher force proves to be problematic for blind-mateable solutions. In addition to maintaining physical contact, each fiber tip within the ferrule must be relatively pristine to ensure the signal is not attenuated through contamination or handling.

A new lensed connector system, discussed below, supports high density optical interconnect demands and addresses the contamination and blind-mate connection concerns.

II. Overview

This paper expands upon the previous lensed connector design work, and builds the necessary loss testing infrastructure to support connector implementation [1-3]. The ferrule builds upon traditional multi-fiber MT technology, but incorporates lenses to provide critical new functionality. The ferrule, shown in Fig. 1, is a monolithic injection-molded part that maintains the traditional MT external dimensions [4]. Therefore, this ferrule can be used with existing MT connector packages, including MPO and other proprietary connector solutions. An array of recessed lenses located on the mating surface of the ferrule collimates the light between mated ferrules (Fig. 1).

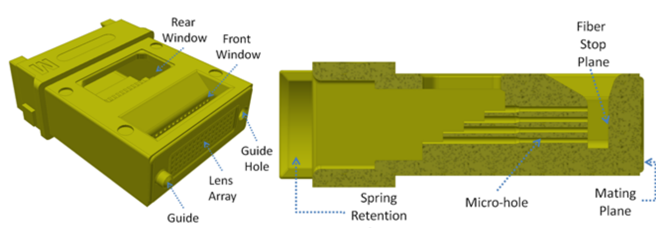

Figure 1: Overview of the lensed ferrule with major features indicated.

Alignment between ferrules is established through a hermaphroditic pin and hole pair in each ferrule and a front mating plane. The conventional metal alignment guide pins of multi-fiber connectors have been eliminated to reduce component costs and complexity. This new architecture also eliminates pin clamps, commonly used in traditional connectors, while incorporating a spring retention seat directly into the rear of the ferrule.

The lens array can accommodate up to 64 lenses in 16 fiber rows. The lenses are recessed below the ferrule mating plane, which sets a controlled distance between the lenses. The recessed design also prevents lens contact damage, but leaves the lens array accessible for inspection or cleaning. Since the only contact between ferrules is a mating plane surrounding the lenses, the spring force is only needed to maintain physical contact between the planes. Unlike traditional MT ferrules where physical contact between fibers necessitates higher spring force for higher fiber counts, a single low-force spring is used regardless of fiber count in the new connector. Therefore, as fiber counts increase, the force required for each connector remains constant. While ganged MPO connectors can cause undesirably high spring forces, the lensed connector allows for high-count ganged connections without a significant increase in spring force. For example, a traditional 12 fiber MT ferrule requires a 10N spring force to maintain physical contact, and that force requirement jumps to 23N for a 24 or higher fiber count. When this is multiplied over ganged connectors, rack structure designs become complicated in order to compensate for the high connection forces. The lensed ferrule requires only a 3N spring force to maintain contact at the lens mating plane, regardless of fiber count. Therefore, racks can contain large ganged assemblies without the penalty of compensating for increased forces.

In order to eliminate the cost and complexity of connector assembly, the traditional pin holder, that may incorporate a spring centering mechanism, has been replaced by a molded spring seating surface at the back of the ferrule. In addition, the embedded fiber design of the ferrule eliminates labor intensive steps involving polishing and interferometry. Connector hardware assembly, visual inspection, and performance testing remain comparable to traditional MPO methods.

III. TERMINATION

Fiber alignment to the lens and guide pin/hole datums is critical to the connector performance. Therefore, microholes comparable to traditional MT infrastructure are used to align the fibers to the lenses. The fiber stop plane sets the fiber tips at the optimal distance for coupling between the transmit and receive fibers and the lens array (Fig. 2). Since the fibers are secured internally in the ferrule, a one-step cleaving process is utilized which eliminates the traditional multi-step polishing process. Optimal fiber cleaving is performed using a laser cleaving process [5]. In comparison, mechanical cleaving produces sharp fiber edges that can generate debris during the termination process. On the other hand, laser cleaving produces a highly repeatable, fracture-free, rounded endface that aids feeding of the fiber into the microholes and reduces debris.

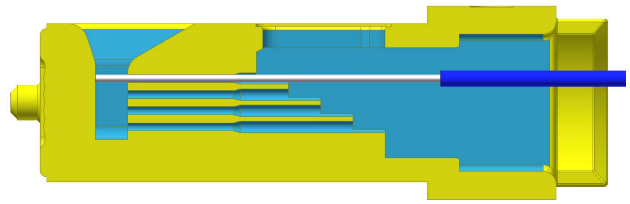

Figure 2: Cross-section of a terminated ferrule, showing fiber (one row populated), microholes, and epoxy locations.

The ferrule has two windows for applying epoxy during termination (Fig. 2). Epoxy is first dispensed in the front window and allowed to wick through the microholes to ensure optimal epoxy coverage of the fiber tips. Since epoxy is present in the optical path, it is a critical component of the overall ferrule performance; the epoxy must be both optically transmissive and index-matched. The fiber stop plane sets the ideal location of the fiber tip during termination, but in practice, not all fibers may contact the fiber stop plane due to variation in cleave length and fiber co-planarity. This gap is referred to as fiber pullback, and can potentially reduce optical coupling between the mated pairs. Index-matching the epoxy to the fiber minimizes the coupling loss and eliminates Fresnel reflections at the surface.

In addition to the optical requirements, selection of the epoxy involved optimizing shrink, CTE match to the ferrule substrate, proper viscosity, and adhesion. Epoxy preparation and curing procedures have been developed and tested in order to minimize air bubbles and provide consistent mix for repeatable termination. Results of these tests are evident in the environmental qualification results presented later in this paper.

During termination, fibers are mechanically stripped and laser cleaved; epoxy is then applied to the front epoxy window. Once the epoxy has wicked through the holes, the fiber is inserted and pushed forward until it contacts the fiber stop plane. At this point, more epoxy is added to the front epoxy window as needed, and the rear epoxy window is filled. The ferrule is then placed in a curing oven and a force is applied to the ferrule body to ensure that the fiber pullback is minimized during curing. Termination is complete after the thermal curing cycle is finished, since no secondary polishing steps are needed.

IV. THEORETICAL MODELING

The ferrule lens is designed to expand and collimate the light, which reduces the sensitivity to both contamination and alignment. The collimated beam, at 180µm in diameter, is thirteen times larger in area than a traditional 50µm core fiber, and therefore is significantly less sensitive to coupling alignment. Lens optimization was performed in Zemax and was then followed up with Monte Carlo simulations to study and reduce the ferrule sensitivity to possible molding or termination variations. The lens optimization was studied using a lensed ferrule pair, as shown in Fig. 3, thereby minimizing ferrule sensitivities in both Tx and Rx

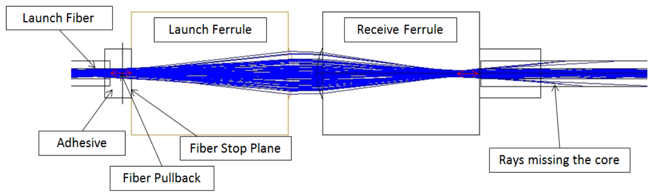

Figure 3: Zemax modeling optimization used a lensed ferrule mated pair to optimize both Tx and Rx configurations.

configurations. Fiber pullback has been modeled as a mated pair; Fig. 4 shows the insertion loss performance of a mated pair with fiber pullback in either the launch or receive end. It is important to note the additive effect of fiber pullback. For example, a single connector with 100µm fiber pullback is equivalent in either transmit or receive, and is the same as a mated pair with each connector having 50µm of pullback.

Back-reflection in a fiber optic connector can impact system link performance [6]. While the ferrule has several interfaces that may cause back-reflection, each interface is either attenuated with index matching epoxy or is curved, which minimizes coupling of the reflected light back into the fiber. The terminated ferrule optical model includes reflection calculations at the fiber tip, fiber stop plane, and lens plane. After including absorption and coupling losses into the model, the calculated back-reflection is -26.7 dB [7]. Empirical data presented later, in Fig. 10, shows an average measured back-reflection of -26.2 dB.

V. CONNECTOR CHARACTERIZATION

A. *Insertion Loss Testing*

Standard fiber optic connector test methodologies, such as insertion loss and back-reflection [8-10], are equally applicable to the new lensed ferrule technology and can be implemented with conventional fiber optic measurement equipment. As with all multimode applications, insertion loss performance is sensitive to encircled flux (EF) launch conditions and should be verified at the last physical contact

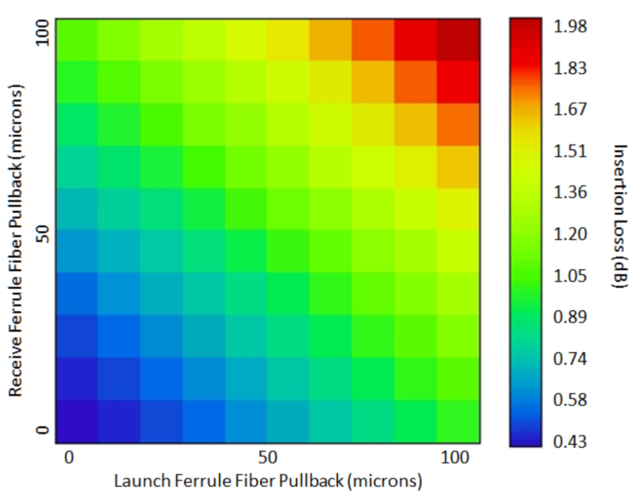

Figure 4: Theoretical modeling of the impact of fiber pullback in either launch or receive configuations in an ideal mated ferrule pair.

connector [11]. A known launch jumper acts as an intermediary between the verified EF connection and the device under test (DUT). The reference lens ferrule is then placed in front of the detector and the loss test system zeroed to establish the reference condition. The device under test is then mated to the reference ferrule and then measured. The first DUT measurement establishes the insertion loss through the mated lens ferrule connection. If a symmetric jumper is tested which has lensed ferrules on both ends, the DUT jumper is simply flipped and remeasured to benchmark the performance of the other end of the DUT (Fig. 5).

While the test methodology is similar to conventional testing, there are reflections that occur at the connector interfaces (IL_{refl}) that must be taken into account. A traditional MT connector has reflections that occur at the air-to-glass interface, but when physical contact occurs during mating, the interface is effectively negated (Fig. 6a). The Fresnel reflection (f_1) is included in the reference value recorded by the system. However, when the DUT is mated to it, both the f_1 and f_2 interface reflections become zero, since the air interface is eliminated by the glass-to-glass physical contact. However, a reflection (f_3) comparable to f_1 has been introduced, so the total reflections in the measurement system remains constant and correct as $IL_{refl}=f_3$.

However, when a lensed ferrule is referenced and measured (Fig. 6b), there is no physical contact connector to change the reflection interfaces. Therefore, during the reference stage, f_4 is recorded as part of the reference. When the DUT is mated, f_4 remains a non-zero number, and f_5 and f_6 reflections are introduced.

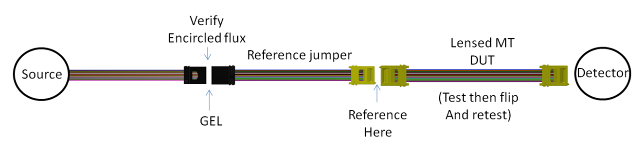

Figure 5: Test configuration for characterizing insertion loss performance.

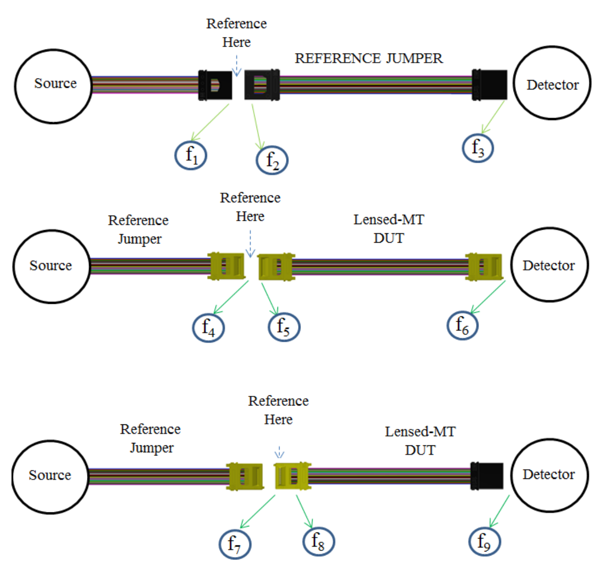

Figure 6: Fresnel reflection occurances in different muti-fiber ferrules: a) MT to MT, b) lensed to lensed (symmetric), c) lensed to MT (hybrid).

As a result, the measured reflection component of the insertion loss becomes:

$$IL_{refl} = f_5 + f_6, \text{ where } f_5 = f_6 \quad (1)$$

$$\therefore IL_{refl} = 2 \times f_5. \quad (2)$$

If a hybrid jumper consisting of a lensed ferrule and MT ferrule is measured (Fig. 6c), f_7 remains non-zero as with the lensed ferrule measurement in Fig. 6b. Similarly, the reflection at f_8 remains the same, but the reflection introduced at f_9 is a glass-to-air interface rather than the plastic-to-air interface, and is therefore different, so the measured reflection component of the insertion loss is:

$$IL_{refl} = f_8 + f_9. \quad (3)$$

Therefore, when comparing insertion loss performance between lensed connectors, it is critical to understand the ferrule types and take the potentially different IL_{refl} value into consideration. Table 1 displays typical values expected for MT and lensed ferrule reflections. From the table, it is evident that adding anti-reflection (AR) coatings to the lensed ferrule endfaces can provide a significant improvement in connector insertion loss performance; all empirical data presented in this paper is for uncoated ferrules.

Based on the expected values from Table 1, the connector insertion loss performance is specified as < 1.2 dB for each channel in a mated pair connection for a symmetric jumper, as shown in Fig. 6b. If the symmetric configuration were to be replaced with a hybrid jumper (Fig. 6c), the measured results would be 0.13 dB lower due to the difference between the MT and lensed reflection values ($f_{n, unmated}$) of Table 1. Typical production data for standard symmetric lensed ferrule jumpers is shown in Fig. 7.

TABLE 1: FRESNEL REFLECTIONS FROM THE ENDFACE FOR DIFFERENT FERRULES AND AR COATINGS

Product	$f_{n, unmated}$	$f_{n, mated}$
MM MT Ferrule	0.16 dB	0.00 dB
Lensed Ferrule	0.29 dB	0.29 dB
Lensed Ferrule with AR Coating	0.06 dB	0.06 dB

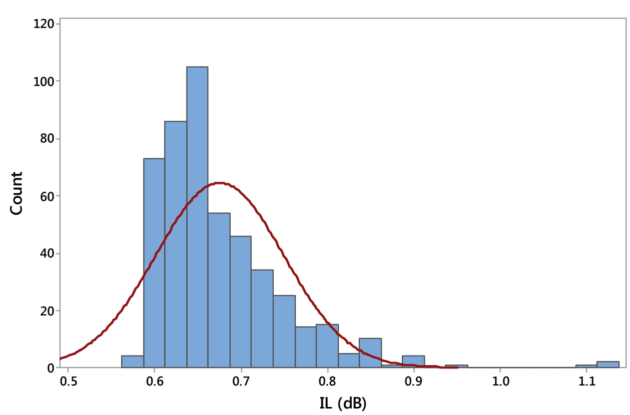

Figure 7: Typical distribution of insertion loss data for symmetric lensed ferrule (non-AR coated) jumpers (N = 480, mean = 0.68 dB).

B. Back-reflection Testing

Back-reflection performance can be quantified in a method comparable to traditional fiber optic connector testing. Back-reflection testing can be performed with the same reference jumper used for the insertion loss testing, which helps minimize changes in the testing configuration. In a traditional MT jumper back-reflection measurement, the last reference face is eliminated through either mandrel-wrapping or use of a gel block. This is necessary, as otherwise the final reflection will substantially reduce the dynamic range of the measurement due to the flat glass-to-air reflection from the final MT.

In a lensed ferrule, the Fresnel reflection off the final surface originates at the curved lens face, so less reflected light is coupled back into the fiber. Therefore, the final reflection does not significantly impact the dynamic range of the test system, and the gel block is not necessary at the last interface. With the endface unterminated, the reference back-reflection remains around -29 dB, which is sufficient for subsequent testing.

Once referencing is complete, the DUT jumper is connected and measured, as shown in Fig. 8. If a symmetric lensed jumper is being measured (Fig. 8b), the lensed ferrule at the final connection can also be left unterminated. As with the reference connection, only an insignificant amount of light is coupled back through the system and does not impact the DUT connection measurement. However, if a hybrid jumper is being characterized (Fig. 8a), the flat glass-to-air interface at the fiber tip will produce high reflections and must be terminated. As was discussed in the theoretical modeling section previously, back-reflection values of -26.7 dB are expected. Typical back-reflection values, shown in Fig. 9, validate the theoretical modeling with a measured mean of -26.2 dB.

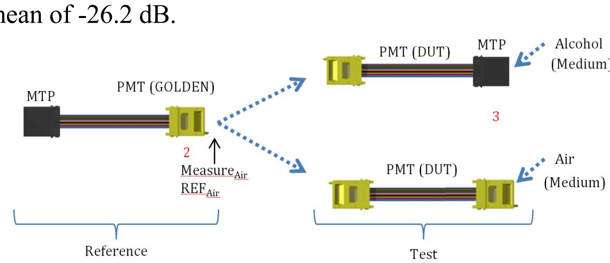

Figure 8: Setup for performing back-reflection testing of the lensed ferrule using either a) hybrid jumper or b) symmetric lensed ferrule jumper.

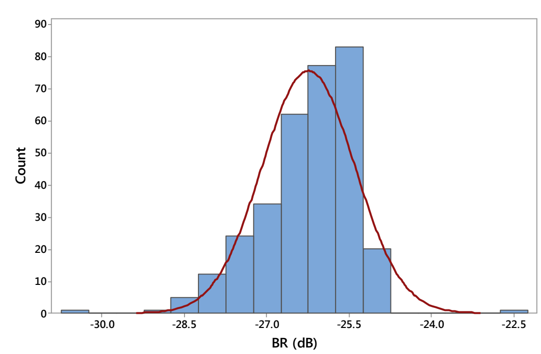

Figure 9: Typical BR data for symmetric lensed ferrule jumpers (N = 320, mean = -26.2 dB).

VI. FAILURE MECHANISMS

While the lensed ferrule's expanded beam is designed to minimize sensitivity to debris, there are still variables that can impact the final connector performance. Within the ferrule, termination errors such as fiber pullback from the stop plane or air bubbles in the optical path will impact performance. External to the termination, debris or scratches on the lenses can impact performance if the damage is large enough. Common failure mechanisms were studied for sensitivity to connector performance and are addressed below.

A. *Fiber Pullback*

As discussed previously, theoretical modeling demonstrated that fiber pullback from the fiber stop plane may impact the coupling between the mated pairs and therefore have an impact on insertion loss. In order to empirically quantify the effects of fiber pullback, ferrules were terminated with controlled gaps at the fiber stop plane. Testing pullback jumpers for insertion loss in both launch and receive configurations confirmed the effects of pullback are symmetric for either end of the mated pair, as previously demonstrated in theoretical modeling (Fig. 4). As stated previously, the pullback is additive across the connection. Fig. 10 plots cumulative fiber pullback for a mated pair in relation to insertion loss performance. For pullback gaps of less than 175µm, there is no significant impact on insertion loss. Therefore, on a single given connection, any fiber pullback of less than 50µm is irrelevant. This is consistent with the theoretical modeling results presented previously.

B. *Air Gaps/Bubbles*

Back-reflection performance of the connector is predicated on having index-matching epoxy in the optical path between the fiber tips and the fiber stop plane. The connector will be sensitive to air bubbles trapped in the optical path. In order to study the impact, parts were terminated with a controlled 50µm air gap in the optical path with no epoxy present. Unlike the typical back-reflection values presented in Fig. 9 that averaged -26 dB, an air gap causes the back-reflection to change to -14 dB. Using the back-reflection methodology presented previously, an air gap located in the DUT at either location A or B (Fig. 11) will yield the same back-reflection performance of -14 dB.

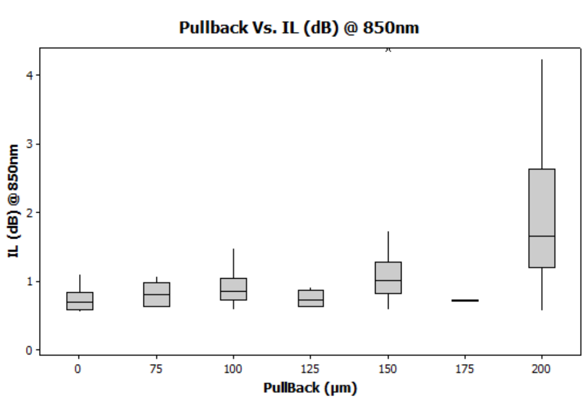

Figure 10: The effect of fiber pullback on insertion loss performance.

C. *Lens Contamination*

Since the expanded beam lensed ferrule has a spot area thirteen times larger than the 50µm core of a fiber connection, contamination in the optical path has minimal impact on insertion loss performance. To study the sensitivity of insertion loss to contamination, connectors were deliberately contaminated with excessive oil (Fig. 12) and Arizona road dust (Fig. 13). In each case, typical ferrules were terminated, cleaned, and tested for insertion loss. Each ferrule endface was then deliberately contaminated and insertion loss was remeasured. Finally, the endface was cleaned with a fiber optic cleaner and insertion loss was remeasured. In each case, the contamination had minimal impact on performance and returned to original performance after cleaning (Fig. 12, 13).

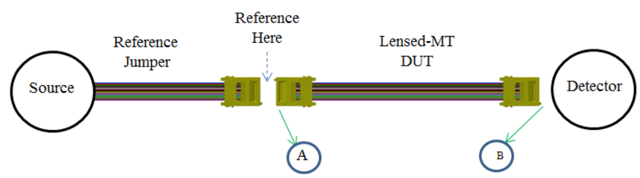

Figure 11: Test air gap locations in a lensed ferrule DUT.

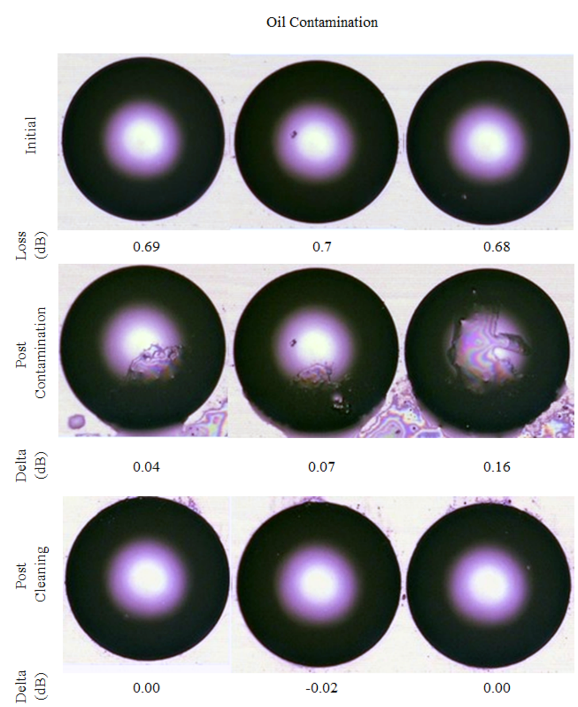

Figure 12: a) Ferrule lenses and insertion loss performance, b) change in insertion loss after deliberate oil contamination, and c) return to initial performance after cleaning.

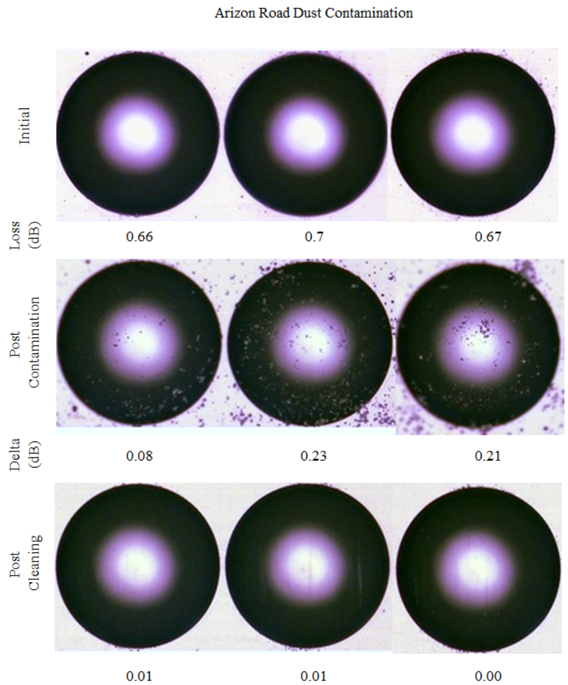

Figure 13: a) Ferrule lenses and insertion loss performance, b) change in insertion loss after deliberate road dust contamination, and c) return to initial performance after cleaning.

D. *Lens Scratches and Digs*

While the impact of scratches will be minimal due to the expanded beam nature of the lensed ferrule, parts were scratched and then characterized for both insertion loss and back-reflection performance. Fig. 14 shows parts with severe damage to the ferrule endface, and yet for every channel both insertion loss and back-reflection met ferrule specifications.

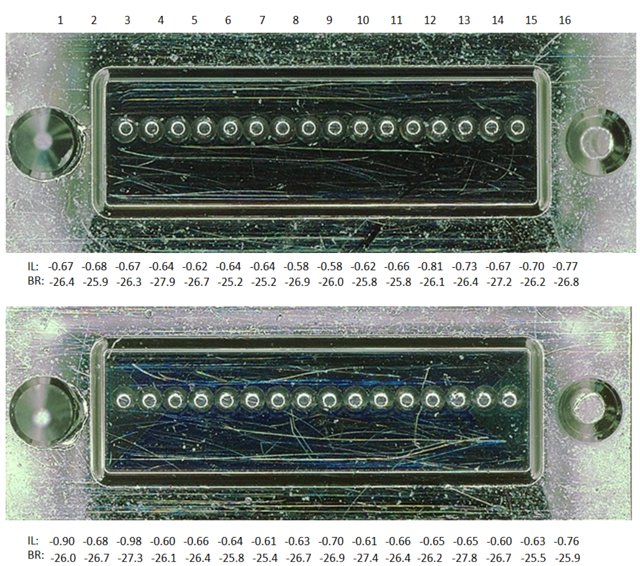

Figure 14: Despite excessive scratches, both insertion loss and back-reflection performance are well within the expected nominal range, as the expanded beam of the lensed ferrule is insensitive to scratches.

VII. QUALIFICATION

In order to investigate long-term performance, assembled connectors were exposed to a battery of environmental and mechanical tests:

- Uncontrolled thermal aging: 85°C, 7 days
- Controlled humidity aging: 40°C/95%RH, 7 days
- Uncontrolled thermal cycling: -40°C to 75°C, 7 days (21 cycles)
- Uncontrolled dry-out: 75°C, 1 day
- Vibration (2 hours per axis, 10 to 55 Hz at 45 Hz/ minute)
- Durability (1000 mates)

A. *Environmental Results*

Mated pairs of lensed ferrule jumpers were exposed to all the environmental conditions listed above. Fig. 15 shows the insertion loss distribution both before and after the environmental testing was complete; there was no significant degradation in performance and no channel changed by more than 0.17 dB at 850nm over the full expanse of testing. Furthermore, every channel continued to pass back-reflection testing after the environmental exposure, indicating adhesion between the fibers and fiber stop plane remained intact.

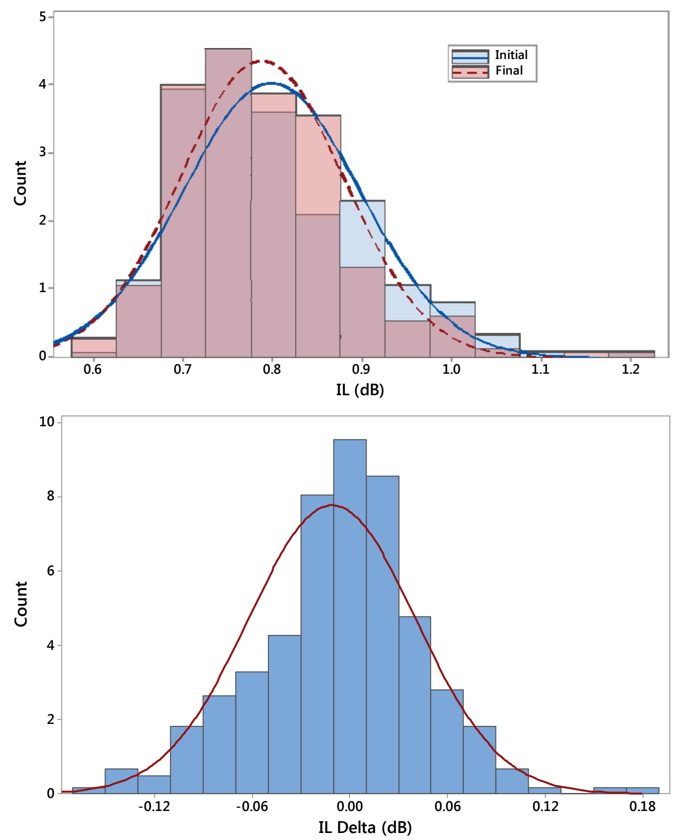

Figure 15: a) Histogram of initial and final insertion loss performance after 22 days of environmental exposure (N = 304, Initial IL mean = 0.80 dB, Final IL mean = 0.79 dB), b) distribution of the channel by channel change in insertion loss performance (N = 304, mean = 0.01 dB).

B. *Mechanical Results*

After environmental exposure, a six hour vibration test (10 Hz to 55 Hz) was performed. The jumpers were then mated 1000 times to test durability, with no cleaning in between each mate. After all environmental and mechanical tests, the average of the insertion loss deviation from the initial, pre-environmental insertion loss was < 0.01 dB. Furthermore, back-reflection results remained above specification through all tests.

VIII. SUMMARY

Lensed ferrules offer a viable solution for emerging high density applications. Expanded beam ferrules solve the problem of limited connector endface access in backplane and ganged applications, while reducing connector mating forces at the same time. Empirical results were presented to validate the theoretical optical modeling. Finally, environmental and mechanical qualification testing demonstrated the long-term reliability of the expanded beam connector.

REFERENCES

[1] D. Childers, E. Childers, J. Graham, and M. Hughes, "Next-generation, high-density, low-cost, multimode optical backplane interconnect," Proc. SPIE 8267, Optoelectronic Interconnects XII, February 9, 2012.

[2] D. Childers, and M. Hughes, "High density, low cost, no-polish optical ferrule," IEEE Optical Interconnects Conference, 2013.

[3] M. Hughes, D. Childers, J. Graham, S. Lutz, and T. Satake, "Multi-fiber connector technologies," Optical Fiber Communication Conference, 2015.

[4] IEC TC 86/SC 86B, "Fibre optic connector interfaces - part 5: type mt connector family," IEC 61754-5:2005, July 2005.

[5] D. Childers, E. Childers, J. Graham, M. Hughes, D. Schoellner, and A. Ugolini, "Miniature detachable photonic turn connector for optical module interface," IEEE 61st Electronic Components and Technology Conference, pp.1922-1927, May 31 2011-June 3 2011.

[6] J. L. Gimlett, and N. K. Cheung, "Effects of phase-to-intensity noise conversion by multiple reflections on gigabit-per-second dfb laser transmission systems," Journal of Lightwave Technology, , vol.7, no.6, pp.888-895, Jun 1989.

[7] T. Satake, D. Chiders, M. Hughes, J. Wakjira, and E. Childers, "Return loss performance of lensed plastic mm 36-fiber connector for data center applications," Proceedings of the Society Conference of IEICE, 2013.

[8] Telecommunications Industry Association (TIA), "ANSI/TIA-568-C.0", February 2009.

[9] Telecommunications Industry Association (TIA), "ANSI/TIA-568-C.0-2", August 2012.

[10] Telecommunications Industry Association (TIA), "ANSI/TIA-568.3-D", 2016.

[11] IEC, "IEC 61280-4-1:2009, Fibre-optic communication subsystem test procedures - part 4-1: installed cable plant - multimode attenuation measurement," June, 2009.