S. Chuang, D. Schoellner, A. Ugolini, J. Wakjira, and G. Wolf,
"Development and Qualification of a Mechanical-Optical Interface for Parallel Optics Links",
Photonics West Optical Interconnects XV, Proc. SPIE 9368, 936837 (2015).

Development and Qualification of a Mechanical-Optical Interface for Parallel Optics Links

S. Chuang, D. Schoellner, A. Ugolini, J. Wakjira, G. Wolf
US Conec, Ltd. 1138 25th St SE, Hickory NC, 28602

ABSTRACT

As parallel optics applications continue to expand, there remains a need for an effective coupling interface between the board-level active components and the passive components of the network. While mid-board level photonic turn connectors are available, coupling interfaces are generally not available outside of proprietary solutions. Development of a general mechanical-optical coupling interface opens the door for broader parallel optics implementation.

An interface for use between the optical transmitter and the photonic turn connector is introduced. The interface is a monolithic injection molded component with an array of collimating lenses to couple efficiently with common VCSEL/PD designs. The component has precise epoxy control features to manage epoxy bond-line thickness and strength. Suitable UV and thermal epoxies have been qualified for effective die bond placement of the component in the VCSEL/PD environment.

Environmental and mechanical performance of the component to industry-standard qualification requirements are reviewed, and tensile force testing and durability results validate the mechanical characteristics of the interface.

Keywords: mechanical-optical interface, photonic turn connector, VCSEL, die bonding, epoxy, transceiver, lens array, coupling efficiency, environmental testing

1. INTRODUCTION

As VCSELs and PD have matured over the past several years, parallel optics are driving higher data rates, enabling a rapid expansion in parallel optics applications. While traditional parallel optics implementations (SNAP12, QSFP, etc.) provide improvements in card-edge space and data rates, mid-board interconnects are necessary for the highest levels of data rates [1 2]. Miniature parallel photonic light-turn (PLT) connectors that efficiently transmit vertically-emitted signals from the mid-board optics to card-edge connectors have been developed and are commercially available [3 4 5 6]. However, the board-mounted mechanical-optical interface (MOI) between the VCSEL/PD and the PLT connectors often remain proprietary and expensive. Development of a generic MOI to expedite coupling opens the door for broader parallel optics implementation; pluggable modules, active optical cables, and embedded modules all use optical arrays and require an effective coupling interface between the VCSELs and the PLT connectors.

A general MOI interface for use between the VCSEL/PD and the PLT connector has been developed; the interface is a monolithic injection molded component with an array of collimating lenses to efficiently couple a wide variety of VCSELs and PDs. The component has precise epoxy control features to manage epoxy bond-line thickness and strength, while incorporating clearance features for most common chip drivers, wire-bond footprints, and AOC heat-sinking requirements. The component has been designed to be compatible with traditional die bonding equipment; die bonding strategies and epoxy adhesion results will be addressed below.

2. GEOMETRY

2.1 Background

PLT connectors have already been prevalent in high-speed mid-board transceiver applications for several years [7 8 9 10]. The PLT connector consists of a precision molded ferrule incorporating a monolithic array of total internal reflection (TIR) lenses which redirect the light path approximately 90° to the fiber axis, facilitating perpendicular mating of the connector (Figure 1). Two guide posts on the PLT ferrule act as the mechanical datum for aligning the PLT connector to the VCSEL/PD optical path. The PLT ferrule inserts into a connector housing; in addition to providing protection for the ferrule TIR lenses, the PLT housing has two latches that are used to mechanically secure the PLT connector to the board-mounted MOI. Relying on the latch and post system of the PLT connector for the MOI connection means that the PLT connector can easily and safely be removed and reconnected to the board-level optics repeatedly, which allows for replacement of connectors for different fiber architecture or for cleaning and debugging. In the PLT ferrule, 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 ferrule polishing and interferometry requirements. Several different PLT housings are available to support different fiber cabling requirements; both loose round cable and traditional ribbon are supported and the latches mate to the PLT connector and MOI interchangeably.

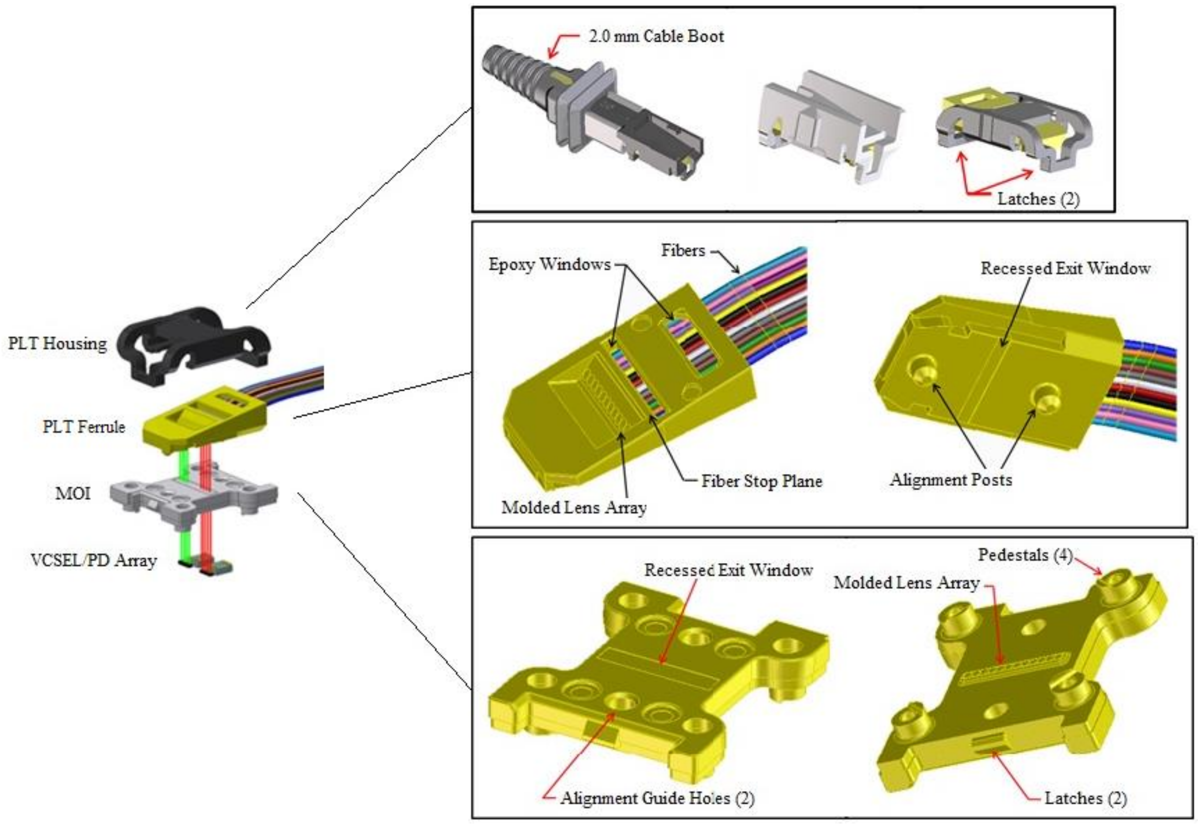

Figure 1. Assembly of the PLT housing, PLT ferrule, MOI, and VCSEL/PD to modularly couple light from the board-level optics to fiber cables. Inset images show a) variations on PLT housings that support both round loose cable fiber and ribbon fiber, b) critical features in the PLT ferrule, and c) critical features on the MOI.

2.2 MOI Geometry

The MOI's two alignment guide holes accept the matching pins from the PLT ferrule and the two latch-keys mate to the connector housing, as shown in Figure 2. 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. Together, the PLT and MOI components provide a stable platform for a rematable connector with the micron-level repeatability needed for transceiver applications [11].

The MOI has an array of lenses that delivers direct coupling between the active board-level optics and the PLT connector, and provides a common platform for the connector seating, regardless of vendor specific active optics. In the transmit configuration, the output from each VCSEL transmitter is collimated by the MOI for transmission into the PLT connector, where the light is focused onto the included multimode fiber. In the receive configuration, the nearly collimated output from the PLT connector is focused by the MOI lens onto the PD.

3. ALIGNMENT AND DIE BONDING

3.1 Alignment Sensitivity

In order to accommodate as many possible VCSEL/PD variations as possible, an industry survey of VCSEL/PD parameters was initiated. It quickly became clear that while there is a relatively small range of VCSEL optical values, the corresponding driver, wire-bond, amplifier and copper trace routing implementations vary considerably. Drivers and wire-bonds occupy considerable area around the optical dies, so both the vertical and lateral clearance around the board optics was maximized. VCSELs emissions are typically highly divergent, and that divergence angle puts an upper limit on the vertical clearance height of the MOI lens; the MOI must capture the VCSEL light before the light diverges such that channel crosstalk begins to occur. The resulting clearance heights are shown in Figure 2.

While standard VCSEL arrays cover a broad range of applications, commercially available VCSEL and PD optical parameters are generally similar. Working with VCSEL and PD manufacturers, the following design parameter windows were settled on for the MOI design optimization. The lens prescription was then optimized for simultaneous Tx and Rx performance. The full model provides expected insertion loss performance for Tx, Rx, and full system links using Monte Carlo trials, and the results have been validated through empirical link loss testing [12].

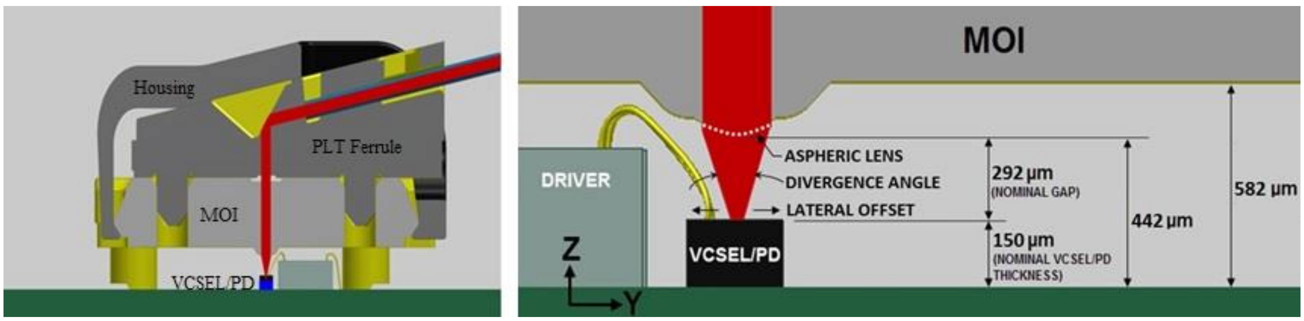

Figure 2. Assembly of the PLT housing and ferrule with the MOI on the circuit board. Light path between the VCSEL/PD and fiber, through the MOI and PLT ferrule is indicated.

Table 1. VCSEL and PD criteria used for MOI optical optimization.

	VCSEL Die Height	VCSEL Aperture Diameter	VCSEL Divergence Angle ($1/e^2$)	PD Die Height	PD Aperture Diameter
Nominal	150 µm	8 µm	25°	150 µm	35 µm
Max	200 µm	8 µm	32°	200 µm	55 µm
Min	130 µm	6 µm	20°	120 µm	30 µm

3.2 Die Bonding Alignment

While the lens optimization has been performed to minimize the sensitivity to alignment offsets between the VCSEL and MOI lens, it is still critical to align the parts as close to nominal as possible. For the nominal conditions of Table 1, a lateral misalignment between VCSEL/PD die and MOI lens of less than 10 µm causes no significant degradation in system insertion loss performance. To cover all the cases of Table 1 with no significant insertion loss degradation, an alignment of ±5 µm is necessary, which is still reasonable with a typical die bonder. Table 2 shows the average expected insertion loss for each link based on Monte Carlo simulations using the alignment and VCSEL/PD optical parameter variables of Table 3. A full discussion of the sensitivity of each variable and explanation of the results is available, including empirical results validating the die bonding and insertion loss calculations [12].

Table 2. Expected average insertion loss performance from Monte Carlo simulations.

Tx Average (dB)	Rx Average (dB)	Total link Average (dB)
1.21	1.09	2.30

Table 3. Variables and values used for Monte Carlo simulations for MOI performance.

Tolerance Item	Nominal	Min	Max
VCSEL to MOI Lens - Lateral Offset	0 µm	-10 µm	+10 µm
VCSEL to MOI Lens - Distance	292 mm	272 µm	312 µm
VCSEL to MOI Lens - Tilt	0 °	- 1°	+ 1°
VCSEL Beam - Divergence Angle	25 °	20°	32°
VCSEL Aperture Size	8 µm		
PD to MOI Lens - Lateral Offset	0 µm	-10 µm	+10 µm
PD to MOI Lens - Distance	292 mm	272 µm	312 µm
PD to MOI Lens - Tilt	0 °	- 1°	+ 1°
PD Aperture Size	55 µm		

Lateral alignment of the MOI to the VCSEL/PD die is controlled by aligning the MOI lenses to the optical dies. Figure 3 shows a bird's-eye of both the top and bottom of the MOI. While the lenses are visible through the exit window, aligning the lenses through the part can be error prone, since any angular misalignment of the part during die pickup will be magnified and cause an offset between the lenses and die. Instead, it is recommended to use a direct view of the lens; this is a commonly available function with die bonding equipment either through the use of a stage that pivots the part for a split view during alignment or via a fiducial alignment feature if a direct view is not viable. In either case, alignment to within 1/3 of the tolerances assumed in Table 3 has been shown to be quite reasonable [12].

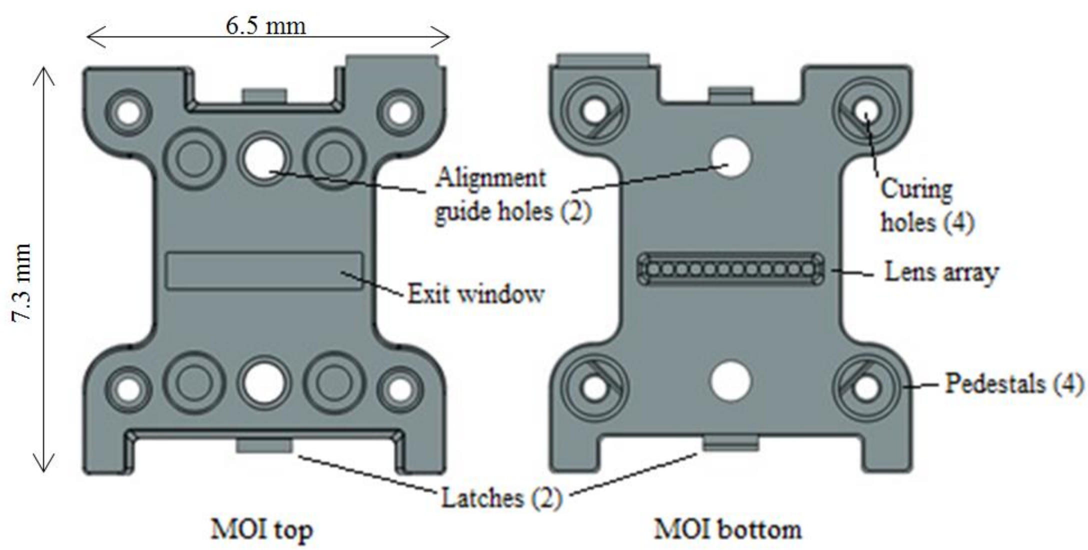

Figure 3. Bird's-eye view of MOI top and bottom, with critical features indicated.

While many die bonders are not as accurate at vertical positioning, the MOI is highly tolerant to vertical misalignment between the MOI and optical die (Table 3). The four pedestals provide sufficient vertical control between the circuit board and the MOI lens such that vertical positional tolerance between the die and MOI is not a concern. As die bonders have a wide range of contact forces that can be applied to hold the component in place during bonding, testing was performed to determine the maximum applicable force before deformation occurred in the MOI pedestals. MOIs were placed between parallel metal plates that could be compressed with a vise, with a force gage attached to determine applied force and a digital microscope to determine when compression of the component began. There was no visible damage, either elastic or permanent, below 3 lbs. on any of the parts tested. Most die bonders can hit minimal application forces less than 1/10th of that value without any concern.

4. ADHESION

Since the MOI is placed via die bonder, it is necessary to adhere the component in place quickly in a production environment. Therefore, the part and processes have been designed such that UV-curable epoxies can be used to quickly lock the component in place before a secondary epoxy is applied later to ensure structural integrity.

4.1 Epoxy Control

While the vertical alignment is not as critical from an optical performance perspective, vertical placement does play an important role in epoxy bond-line thickness and epoxy placement, and therefore features were designed into the component to control the epoxy location and bond-line thickness. The four pedestals indicated in Figure 3 contact the circuit board directly and straddle the optical dies. Each pedestal contains both a vertical step across the contact pad of the pedestal and a vertical cylinder running through the length of the MOI down the pedestal; these features are visible in both Figure 1 and Figure 2. When the MOI is placed on the circuit board, each pedestal step creates a 100 µm gap where a UV-curable epoxy is used to lock the MOI in place quickly during alignment. Each step is oriented such that the epoxy flow is kept away from critical optical die features; any epoxy movement will be outward from the MOI into non-critical areas. A UV-curable epoxy requires reasonably uniform exposure from the light source; in order to eliminate much of the shading caused by the steps in the pedestals, the cylinders serve as light-guides to allow adequate light exposure both from the sides as well as the top of the MOI. Furthermore, the channels also help control epoxy flow, as excess epoxy also tends to flow up the channels with the added benefit of larger epoxy contact surface and improved adhesion.

Typically, die bonders apply epoxy either by dipping the component in a shallow bath to apply epoxy to the bottom or via syringe by placing controlled drops directly on the board prior to placing the component. Both methods work well with the MOI; the pedestals are deliberately long enough such that dipping the pedestal steps into an epoxy bath does not contaminate the remainder of the part or the lenses.

4.2 Epoxy Testing

A UV-curable epoxy for die bonding the MOI must adhere well to both the substrate and the MOI, have sufficiently high viscosity or thixotropic indices such that it works for both epoxy dispensing methods, and has a low volumetric shrink so the force does not overcome the vacuum hold of the die bonder and move the MOI during curing. It was determined that a viscosity around 2,000-4,000 cps consistently functioned well for both epoxy application methods and still functioned well with the pedestal epoxy wells.

Epoxy adhesion to the substrate and MOI was tested by placing four consistent drops of the DUT epoxy on an FR4 circuit board and then placing the MOI on top and curing per the manufacturer recommendations. Once the epoxy was cured, the MOI was pulled with a force tester mounted normal to the circuit board and the failure point recorded. The PLT housing can be removed from the MOI with a maximum force of 1.6 pounds, so a base pass/fail value of 3.2 pounds was set for epoxy grading purposes. After testing dozens of epoxies, an epoxy was identified that cured consistently with an average pull force of 4.1 pounds, with the appropriate viscosity range. When combined with the other criteria, such as volumetric shrink, a urethane acrylate epoxy was found that satisfied all the criteria (NextGen Adhesives NGAC UV-AB36-HV).

However, while the identified epoxy showed good initial adhesion performance, UV-curable epoxies have historically not shown suitable long-term adhesion performance in fiber optical systems when subjected to enhanced environmental aging. Therefore, the UV epoxy is used as the locking force to secure the MOI during the die bonding, but is not relied on for the final long-term bond strength [11]. For the final adhesive force, traditional thermal cure epoxies used for fiber optic connector systems were tested as a secondary application, using the same shrink, viscosity, and adhesion criteria as above. First, the UV-epoxy was applied and cured with a 365 nm LED source for 30 seconds with a 12mm spot with an irradiance of 300 mW/cm^2. Then, the thermal epoxy was applied to each of the four corners of the MOI and cured in a standard convection oven at 85ºC for 55 minutes. After screening multiple epoxies, two candidates looked promising: Fiber Optic Center's AB9320 and NextGen Adhesive's NGAC-P907-100. Part performance baselines were established using the pull force metric, and then parts were placed in an environmental test chambers for seven days serially each at 85ºC/85%RH, -40ºC/75ºC cycling with 60 minute ramps and 60 minute cycles, 95ºC/95%RH, and finally 110ºC. Starting with sixteen assemblies using each epoxy, at each test four parts from each epoxy were removed from the chamber and tested. The results of Table 4 show the results of the parts run serially through the entire test; clearly both epoxies performed well through the twenty-eight days of extended testing and easily surpass the 3.2 pound requirement established above. Figure 4 displays all of the results taken during and after the twenty-eight days of environmental testing; even after the full serial test all parts were more than three times the required retention spec.

Table 4. Pull force results (in pounds) of MOI from circuit boards as a baseline and after 28 days of environmental testing.

	Average		Minimum	
Epoxy	Baseline	Post-Env	Baseline	Post-Env
907-100	19.7	13.0	15.1	12.4
9320	19.5	10.8	12.7	9.9

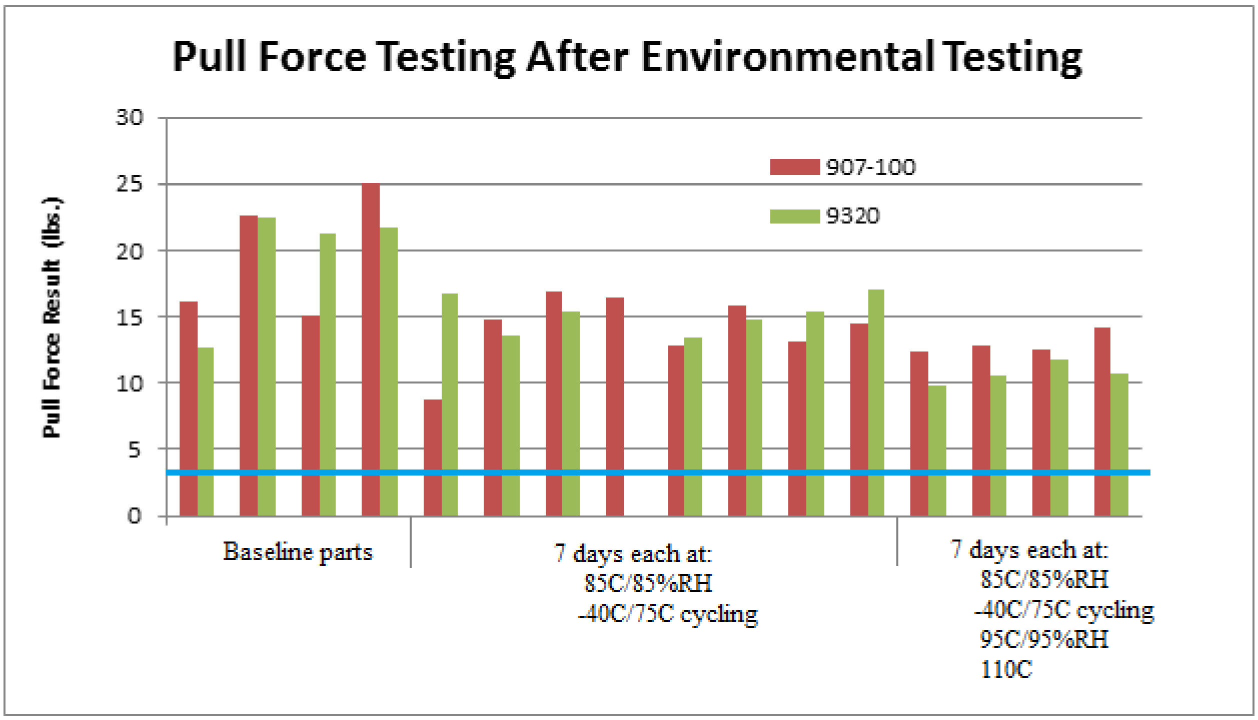

Figure 4. Pull force results (in pounds) of MOI from circuit boards as a baseline and after 28 days of environmental testing. The horizontal line at 3.2 pounds indicates the required force specification.

4.3 Durability

With a viable method to die bond the MOI to the circuit board, mechanical testing of multiple matings to the MOI was tested next. Under normal use, it is anticipated that a MOI component could see several PLT connectors mated to it during testing, fiber routing, cleaning, and prior to the final use in an AOC or similar application. Therefore, four unused MOI components were bonded to circuit boards, and then a PLT connector mated to each one 100 times with no cleaning between each mate. After 50 and 100 mates, images were taken and compared to the initial images; no discernable markings or damage were found on any of the connectors or MOI components after 100 mates.

4.4 Sealing

While the MOI is well attached to the circuit board with the lenses in an unexposed condition and the PLT ferrule lenses are protected by the PLT housing, there are cases where the final assembly may be used in a condensing or harsh environment. In these cases, there is as much concern about the exposed optical die wire bonds and optics as there is with the MOI lenses. In order to protect the entire system, UV-curable gasketing materials were investigated that could seal the entire MOI or even to encapsulate the MOI/PLT connection to the surface of the circuit board to seal all sensitive electrical and optical components. UV-curable gaskets have high viscosities such that wicking below the MOI into sensitive optical area will not occur, are easy to apply, quickly cured before movement or wicking can occur, and generally do not outgas. Two potential candidates, Dymax GA-140 and GA-201 were identified after the initial screening; as both are used for automotive gasketing applications, they appeared to be sufficiently durable. For each of those materials, the epoxy testing regime was repeated; MOI parts were attached to circuit boards with the UV-cure epoxy, and then the gasket material applied around the MOI. The same environmental testing scheme was followed, with four baseline parts of each material and four parts pulled from environmental chambers after a twenty-eight day serial test of seven days each at 85ºC/85%RH, -40ºC/75ºC cycling with 60 minute ramps and 60 minute cycles, 95ºC/95%RH, and finally 110ºC.

While the gasket material has a low holding force, it is important to remember it was selected to seal the surfaces and retain contact; the main retention force would still be provided by the thermal epoxies listed above. However, the thermal epoxy was deliberately omitted from this test such that the sealant was clearly the material under test. As the AB36-HV UV epoxy used to tack the MOI down will not continue to hold securely after the prescribed extreme environmental regime, any measured force after the test is a direct measure of the gasketing material's adhesion to the MOI and circuit board. From Figure 5, it is evident that both gasketing materials survived the environmental testing and are capable of sealing the MOI or the entire MOI/PLT system to protect the MOI and optical dies in harsher environments. In addition, thorough visual inspection after the environmental qual revealed no defects or breaks in any of the gasket surfaces.

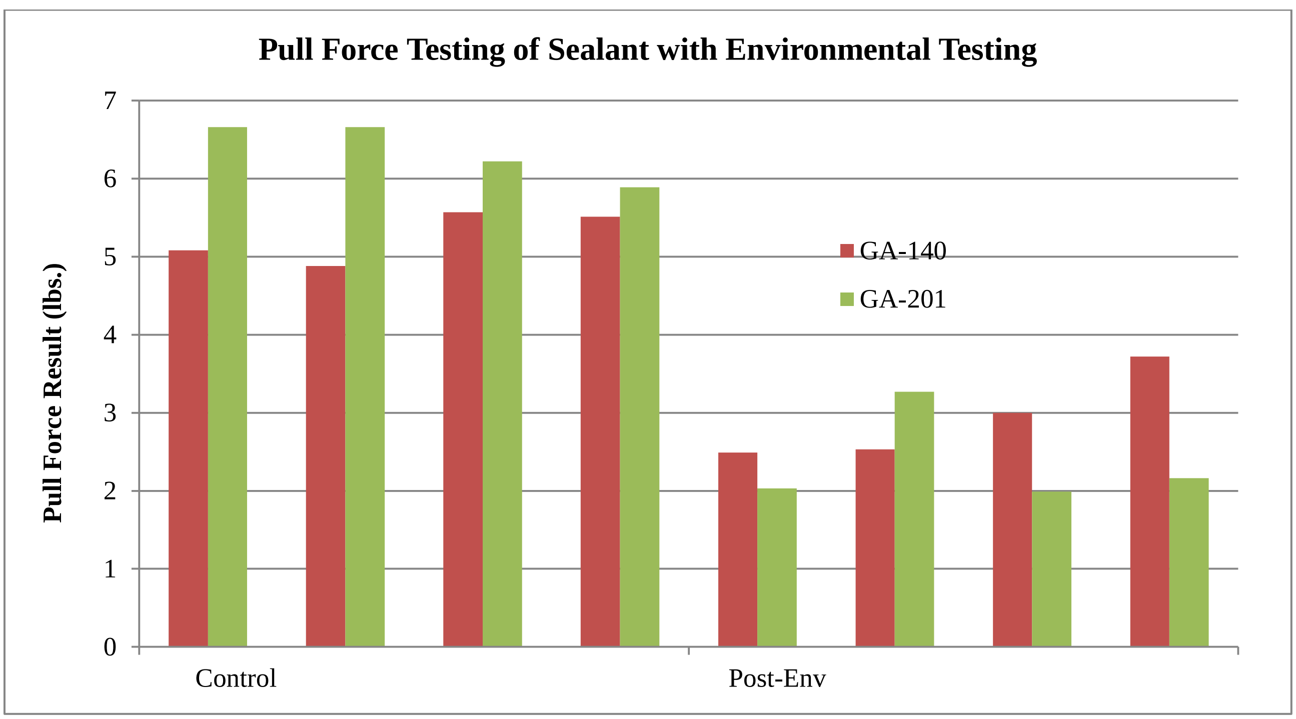

Figure 5. Pull force results (in pounds) of MOI from circuit boards as a room-temperature baseline and after 28 days of environmental testing.

5. SUMMARY

In order to support the expanding demand for mid-board optical interconnects, a mechanical-optical interface (MOI) has been developed as a coupling component between both VCSEL and PD optical dies and the PLT connectors used in passive optical networks. The component has been designed to be compatible with existing die bonding processes and equipment, such that it can be easily incorporated into existing product lines. Placement and bonding techniques have been developed to support the component, and epoxies for both quick tacking and long-term adhesion have been identified and qualified. Furthermore, a gasketing and encapsulating material has been tested for harsh environment conditions.

Future development of the MOI component may include support for higher data rate applications through support for higher channel counts; currently the IEEE 802.3bs working group is developing 16 channel schemes for 400 Gbps applications [13]. As data rates continue to climb, it is expected that PD apertures will shrink and VCSEL beam outputs will further diverge, which may necessitate a new lens prescription to support smaller spot diameter requirements. Similarly, with a different lens prescription, nothing precludes the MOI from supporting coupling for single-mode fiber applications, although the alignment sensitivity analysis would have to be studied carefully.

REFERENCES

[1] Fields, M., “Transceivers and Optical Engines for Computer and Datacenter Interconnects,” OFC/NFOEC 2010, “Special Symposia: Beyond Telecom and Datacom: Optical Interconnects for the Computercom Era", (2010).

[2] Vaughan, D., Hannah, R., and Fields, M., “Applications for Embedded Optic Modules in Data Communications,” 25 March 2011, <http://www.avagotech.com/docs/AV02-2869EN> (6 January 2015).

[3] Childers, E., Graham, J., Hughes, M., Schoellner, D., and Ugolini, A., “Miniature detachable photonic turn connector for optical module interface,” “IEEE 61st Electronic Components and Technology Conference 2011,” (2011).

[4] Hughes, M., Graham, J., Schoellner, D., Childers, D., Childers, E., and Ugolini, A., “Miniature Detachable Photonic Turn Connector for Parallel Optic Transceiver Interface,” OFC/NFOEC 2011, (2011).

[5] Childers, D., Childers, E., Graham, J., and Hughes, M., “Next-generation, high-density, low-cost, multimode optical backplane interconnect,” Proc. SPIE 8267: Optoelectronic Interconnects XII, (2012).

[6] Childers, E., Hastings, D., Schoellner, D., Ugolini, A., and Wakjira, J., “Performance methodologies of a modular miniature photonic turn connector.” Proc. SPIE 8630: Photonics West Optoelectronic Interconnects XIII, (2013).

[7] Benner, A., Kuchta, D., Pepeljugoski, P., Budd, R., Hougham, G., Fasano, B., Marston, K., Bagheri, H., Seminaro, E., Xu, H., Meadowcroft, D., Fields, M., McColloch, L., Robinson, M., Miller, F., Kaneshiro, R., Granger, R., Childers, D., and Childers, E., “Optics for High-Performance Servers and Supercomputers,” OFC 2010: Beyond Telecom and Datacom Symposium III, (2010).

[8] Peng Li, M., Martinez, J., and Vaughn, D., “Transferring High-Speed Data over Long Distances with Combined FPGA and Multichannel Optical Modules,” 21 March 2012, <http://www.avagotech.com/docs/AV02-3383EN> (6 January 2015).

[9] Kuchta, D., Rylyakov, A., Schow, C., Proesel, J., Baks, C., Westbergh, P., Gustavsson, J., and Larsson, A., “64Gb/s Transmission over 57m MMF using an NRZ Modulated 850nm VCSEL,” OFC 2014: Low Power VCSEL Interconnect, (2014).

[10] Iles, G., Jones, J., and Rosea, A., “Experience powering Xilinx Virtex-7 FPGAs,” Topical Workshop on Electronics for Particle Physics, (2013).

[11] Ugolini, A., Childers, E., Hastings, D., Schoellner, D., and Wakjira, J., “Performance Characterization of a Modular Miniature Photonic Turn Connector and Optical Module Interface,” Proceedings of the International Wire & Cable Symposium, (2010).

[12] Chuang, S., Schoellner, D., Ugolini, A., Wakjira, J., Wolf, G., Gandhi, P., and Persaud, A., “Theoretical and empirical qualification of a mechanical-optical interface for parallel optics links,” Proc. SPIE: Photonics West Optical Interconnects XV, (2015).

[13] Kolesar, P., Lingle, R., and Ugolini, A., “400GBASE-SR16 Cabling,” September 2014, <http://www.ieee802.org/3/400GSG/email/pdf2XrN5gMdmE.pdf> (7 January 2015).