

Optical Interconnections using Polymer Waveguides

Optical InterLinks GuideLink™ polymer waveguide technology has demonstrated unique capabilities for rapidly developing custom prototypes through pilot scale production for optical interconnection links. Practical interconnectivity for diverse applications has been demonstrated resolving many of the critical issues normally associated with polymer waveguides including performance, reliability, manufacturability and costs. Current product deliveries include both flexible and substrate bound links as well as a number of functional devices such as splitters, combiners, star couplers and sensors read heads. GuideLink™ technology's developmental maturity is sufficient for practical applications and manufacturing scale up. GuideLink™ products and technology were used to exemplify the potential and developmental status of polymer waveguides in a paper on optical connectivity to be published that provides a good perspective on the market, available technologies and product diversity potential.

The attached paper "Practical Optoelectronic Substrate Connectivity" authored by Bruce L. Booth and Jack Fisher, scheduled to be published in *Printed Circuit Design and Manufacture* magazine, reviews the reawakening need and preferred embodiments for optical interconnections at the board and chip level to overcome high frequency electronic performance limitations and provide enhanced design options. The paper emphasizes the growing interest and attributes inherent with polymer waveguide technology to satisfy industry requirement for optical interconnectivity. It was written from a didactic point of view for electronic board manufacture readers using GuideLink™ technology as the prime example for cost effective reliable practical polymer waveguide interconnection systems. Applications and capabilities of Optical InterLinks GuideLink™ polymer waveguide system are used throughout to exemplify what can currently be achieved with polymer waveguide technology. .

A key point made within the paper is the importance and desirability to start with a self supporting flexible film substrate with encapsulated waveguides that can be pre-machined for connectivity with confirmed high performance meeting specs. This ensures the most cost effective high yield assembly during system installation. For example, installing pre-qualified optical links ready for interconnecting with more expensive board and chip level components avoids potential costly yield loss that could result from constructing waveguide films directly on or within high value boards that would need to be scrapped with loss or remounting of components should the optical link not perform or couple properly.

Optical InterLinks technology is capable of direct waveguide film construction and application on hard or flexible self supporting film substrates allowing substantial preprocessing for desired applications. This creates a broad range of versatile options for dense parallel links and functional devices that are all fully connectorized. They can be readily interfaced or coupled to arrays of solid state components or optical fibers. Prototypes are being delivered to multiple customers spanning numerous end use markets. Pilot manufacturing scale-up is underway for increased production. We believe that GuideLink™ is the leading polymer waveguide solution for providing cost effective and reliable systems meeting critical industry requirements for practical and versatile optical interconnectivity solution.

Bruce L. Booth: President; Optical InterLinks, LLC a Martra Company 1/4/08

Practical Optoelectronic Substrate Connectivity

Authors: Bruce L. Booth and Jack Fisher

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ACKNOWLEDGEMENTS:

Practical Optoelectronic Substrate Connectivity

Authors: Bruce L. Booth and Jack Fisher

INTRODUCTION:

Optical interconnections are under serious consideration for use throughout the backplane and/or motherboard to or from adjoining daughter cards or associated interposer peripheral boards due to increasing costs and adverse performance issues associated with high frequency electronics. A few years back people were talking about “optical interconnect” and “embedded waveguides” especially in the high-speed industry. Then the market changed, aggressive improvements in high frequency copper signal transmission were made, the dot/com crash decimated optical market pull with commensurate technology loss, and the discussion on “opto” declined to almost nothing.

Today however, implementation of optical interconnection technology is reappearing as a method to resolve or reduce the impact of many critical issues associated with the increasingly high frequency data rates beyond 10GHz and aggregate data rates in the terabit/sec realm which is expected to significantly increase overall computing power. Concerns driving photonics are EMI particularly for 10 to 20 Gbps or higher where copper has increasing issues (particularly in aerospace and military environments), interconnecting high input/output-density packages that are reaching toward 1000 channels each at > 10Gbps, minimizing heat dissipation, signal conditioning, and other costs associate with high-speed electronics. In addition photonic interconnections permit system partitioning design options for enhanced performance or size, weight and power improvements that are achieved by separating system components or segments.

Anticipated widespread commercial implementation is predicated on system designs effectively addressing performance, cost, reliability / lifetime / survivability issues and their trade offs for intended applications. This article attempts to provide information on the technology needs and capabilities existing today for board level optical interconnectivity. However, at this point in time the consensus is that widespread commercial deployment of photonic board level interconnections remains in the 2012 time frame and beyond.

For most applications, whether telecommunications, computers, data transmissions, etc., a broad range of optical capabilities must be available to facilitate a complete optical interconnection system yet be compatible and in association with electronic systems as a hybrid configuration. Application-driven capabilities include on-substrate based waveguides, which are optical signal carrying “wires” typically as glass fibers or in films, either on the surface or embedded, off-substrate as flexible and/or bendable links, and with coupling interfaces and connectivity to light sources and photodetectors. In addition, application specific compatibility and reliability must be met for reasonable manufacturing assembly processes, thermal mechanical environmental impact, and lifetime requirements. Substrate connectivity starts from off the backplane or mother board and continues through to the chip level, typically on or associated with daughter boards. The signal must also move between chips on multiple boards and ultimately back out off the motherboard. These same optical capabilities are also applicable to stand alone packaged transmitter and receiver applications and for substrate-based or stand alone functional splitters, star couplers or other components providing functionality. The point being that requirements and capabilities meeting practical substrate based application needs are also essential for a broad range of diverse optical interconnectivity solutions.

This article reviews the generic capabilities for a practical optoelectronic substrate interconnection system, the substrate associated polymer waveguide capabilities and requirements, and evolving practical embodiments under development today using Optical InterLinks GuideLink™ polymer waveguide technology as one of the leading examples for realistic substrate associated optical interconnectivity.

OPTICAL SIGNAL DISTRIBUTION REQUIREMENTS. A broad range of optical capabilities must be utilized to facilitate a complete optical interconnection system from off board to the chip level, between chips on multiple boards and back out off board. Optical fibers and polymer waveguides are providing practical hybrid solutions that begin to meet industry requirements. Both point-to-point optical links and functionality for signal distribution options combined with appropriate connectivity solutions are being explored, prototyped, and implemented. Subsets of these capabilities are being utilized for stand alone off-substrate functional components. Optical InterLinks polymer waveguide technology exemplifies how the critical attributes can and are being met at this point in time for specific application developments and will be used as examples of evolving practical systems. Capabilities for a complete optical interconnection system involve:

1) Optical input and output connections at the edges of the motherboard or backplane. For some time optical fibers have been used to connect at the board edge directly to photo detectors and laser sources where the light is converted to electronic signals for standard distribution via electronic runs and vice versa for the output. Single fiber, multiple fibers in ribbons, or cables are used for these board inputs. The need to overcome issues imposed by copper transmission lines on the board, such as high signal input / output density, EMI, high energy consumption and associated heat dissipation, plus physical constraints such as the forces required to couple high-pin-count density connectors, are increasingly driving the use of optical transmission into the mother board through to the daughter boards.

2) Backplane /mother board (BP/MB) optical signal distribution. Board edge connector coupled optical signals are distributed across the backplane to the daughter board assuming no active components on the BP/MB. Depending on the board size and the length of the optical runs required, either fibers/fiber ribbons or polymer waveguides can be used. Since optical fibers have lower optical loss they are preferred for long runs typically covering > 30 to 100 cm. Fibers will likely be in the form of bundles, or ribbons or increasingly encapsulated in commercially available polyimide sheets pre-arranged in a flexible film package. Fiber shuffles for signal distribution can be mounted on the BP/MB to uniformly route optical I/O between all daughter boards if required. Parallel array polymer waveguide links can be used to distribute signals from short millimeter lengths up to 30 to 50 cm runs depending on optical loss at the wavelengths used and the allowed system loss budget, which for some board systems is in the 10 to 15 dB (~5% signal left) range. Some polymer waveguides also have the advantage that unique functionality like low-loss crossovers for routing, splitters, star couplers for mixing and distributing, and/or combiners can be readily incorporated in planar waveguide films. Both fibers and polymer waveguides films can be attached/bonded to the substrates, be embedded within or between boards or be a flexible off-substrate circuit attached only where needed at the end connecting points. BP/MB optical signal distribution typically provides routing to the right angle oriented daughter boards where the active light sources, detectors and logic chips are located. Of course for a single board system containing active components, the fiber arrays connected at the board edge to fiber or polymer guides for interconnections directly to components throughout the single board.

3) Right angle connectorization at the daughter board (DB) junction with the BP/MB. Right angle board to board connectivity is required to couple light between DBs and BP/MB that interconnect 90 degrees to each other. Low cost high-performance right angle array connectors are critical for this application and considerable efforts have been expended by many groups to achieve a practical cost effective solution compatible with electronic counterparts on the daughter board.

To achieve DB to DB connectivity along the BP/MB, waveguide arrays need to enter the BP/MB connector housing from both directions. To achieve dual directionality typically requires multiple waveguide array interconnects stacked in at least two or more layers to be able to direct signals from daughter card to daughter card along the BP/MB. Use of closely spaced waveguides enables very high-density interconnections within a standard MT form factor or other custom two pin aligned ferrule options.

An MT (multi-terminal) connector is a commonly used fiber optic ribbon connector. With appropriate machining it is modifiable to provide free standing and board edge planar polymer waveguide array coupling alignment. The MT ferrule connector is very popular due to its small form factor and ability to connect 24 channels with 12 per each of two rows or greater numbers with more rows space permitting and maintaining conventional optical fiber 250 microns pitch spacing. Machining modifications enable coupling of up to several hundred closely-spaced polymer waveguides for high density interconnectivity. Typically MT ferrules are inserted into flexible aligning and locking housings to provide a latchable connector tightly holding the coupling interfaces together with a zero air gap for low optical loss. Commercially these latchable housings are sold under different manufacturer's names such as MPX or MPO etc. connectors.

For right angle board-to-board optical interconnections, once the daughter card is inserted the locking mechanism assures a zero air gap interconnect between adjoining ferrules, but with sufficient insertion force flex to be compatible with adjoining electronic pin connectors on the daughter board. This avoids a hard stop upon insertion of a board but still assures good coupling. The natural bend flex of self supporting waveguide films is thus important. On the other hand unique lens configurations are also being explored to provide practical coupling solutions allowing an air gap and more forgiving alignment tolerances. These are useful for high vibration environments.

Both electronic and optical connector housings should have nearly identical height and at least compatible form factors on the edge of the DB and on the BP/MB. Spring loaded latchable housings with internal custom ferrules are the preferred optical configuration choice for these applications at this time. Once the optical signals are on the DB, array routing and optical functionality is again required where polymer waveguides offer unique versatility to distribute signals through the daughter card.

4) Optical signal distribution on the DB or into Tx/Rx link packages. Optical signals on the DB's are distributed directly to components or to small interposer boards for subsequent distribution to and from typically VCSELs (vertical cavity surface emitting lasers) and detector components. Traversing the offset space between the parallel DB and the interposer board requires either flex optical waveguides and edge connectors or lens and I/O mirror arrays to couple across the DB and small board offset air gap. Waveguide array transmitted signals are coupled directly to detectors (PD) or from the VCSELs, both components being close to their amplifiers or driver chips. Increasingly the capability and versatility inherent with polymer waveguides is a prime consideration for DB signal distribution. Some of the enabling capabilities and attributes for polymer waveguides include:

Point-to-point dense arrays as flexible links (unattached except at the terminations) or substrate-attached links or combinations;

The ability to provide complex routing under, over and/or around surface mounted components or, alternatively, the waveguides are embedded between board substrates to be routed from the underside to surface component side;

Functionality including splitters, combiners, star couplers, crossovers to redirect the normally parallel arrays; and

Good coupling with I/O mirrors for out-of-plane component interfaces from below or from above as has been demonstrated with flip-chip or top-surface interfaces respectively.

5) Other Optical Interconnection Systems. Combinations of 1) through 4) taken separately as indicated above are enabling for a number of polymer waveguide optical interconnection applications. In particular, these include separately packaged optically interfaced transmitter/receivers, stand-alone functional components, optical sensor read heads, and biosensors. In addition, custom or conventional ferrule-based connectorization is enabling to interface fiber shuffles and fiber distribution harnesses to boards or components.

BOARD LEVEL POLYMER WAVEGUIDE CREATION–

Versatile and practical interconnection solutions are inherently achievable with optical polymer waveguide technologies that facilitate the distribution requirements summarized previously. In particular, practical cost-effective optical interconnections can and are being created today using typical generic procedures that enable several application embodiments noted below.

GENERIC WAVEGUIDE SYSTEM CREATION PROCEDURE STEPS

- 1) Waveguide design layouts for parallel links and/or functionality are created using waveguide design software such as R-Soft. These designs are then reduced to instructions to write high quality photolithographic masks.
- 2) Polymer material and related constituent's synthesis, purification, mixing/dissolution, filtration, coating, solvent removal or whatever materials prep is required for raw materials and film preparation to provide the lowest optical loss material system to expose/process waveguides.
- 3) Using appropriate process technology to be described in more detail below, waveguides are created with encapsulating protective layers in self-supporting film sheets. We believe this is the preferred practical route to produce useful interconnects as opposed to creating the waveguides on substrates for final application.
- 4) Precise micromachining of the film sheets typically using excimer laser-based high-precision computer workstation micromachining with sub-micron resolution to separate the large number of imaged parts from one exposure and to precisely and reproducibly locate the waveguide array links or functional devices within each film structure. This enables connectorization and optical interfaces to be configured in large numbers. Out-of-plane reflective mirrors are also created and metalized as needed.
- 5) After all connectorization and interfaces are assembled, the links or devices are fully evaluated to assure high-quality performance before installation on the final substrates or in the package. Constructing pre-fabricated self-supporting connectorized guides reduces the potential for high value yield losses. Alternatively, if waveguides are directly created on high-value substrates, defective waveguides would necessitate rework and or scrapping of the entire high value board.
- 6) Final assembly of the optical and electronic components and full quality verification.

This generic procedural sequence to waveguide creation provides a useful understanding of a practical and cost effective route for the development and implementation of polymer optical interconnections aimed at realizable optoelectronic substrate connectivity.

PRACTICAL APPLICATION CONFIGURATIONS

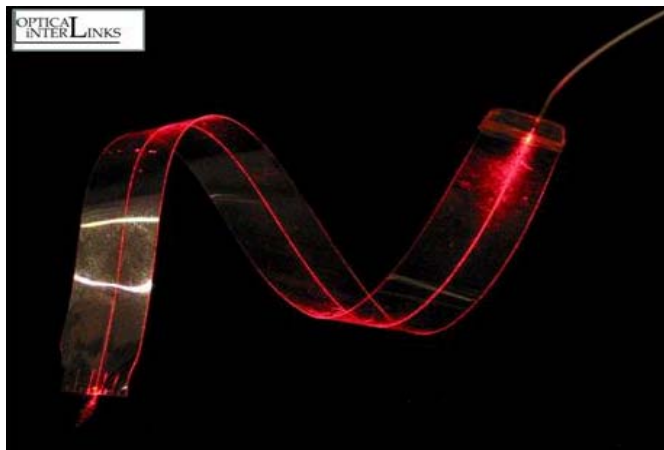


Fig 1: Self Supporting Flexible Waveguide Film: Waveguide films have been exposed with photomasks. This film strip is ~ 25cm long with waveguides on 125 micron centers.

Substrate-surface attached waveguides for board edge-to-chip interfaces or chip-to-chip coupling. Coupling to/from the chip is typically through flip-chip solder bump procedures using out-of-plane I/O mirrors. Solder bumps/balls are used for chip alignment and attaching components to the substrate.

Combinations including on-substrate surfaces as in 1) above going off-surface using flexible jumper style links to connect to the chip top surface. This provides for diverse configurations such as board edge-to-chip, chip-to-chip or chip-to-off-board fiber-array ferrules.

Jumper style interconnectivity on both ends facilitating off-board or device package I/O leading to chip top access, and chip-to-chip options.

Interconnect Options for Parallel Links -- 2

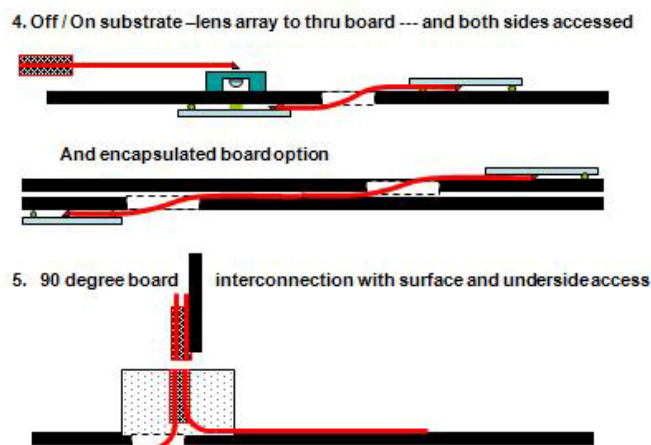


Fig. 3: Similar to and continuing from the previous figure -1 with numbers used in the text coupling examples for 4) waveguide to lens array coupling, links bridging between top and under surfaces for single and dual substrates, and 5) 90 degree interconnectivity for daughter to mother board connections

Waveguide interconnections can be designed and installed with several embodiments compatible with the desired board interconnectivity for back-plane/motherboard routing and coupling to daughter boards or single boards. Interconnectivity to the sources and detectors associated with the electronic chips is facilitated with versatile optical configurations. A flexible yet robust encapsulating film as shown in Figure 1 provides a thermomechanically-stable self-supporting structure.

Versatile designs and flexible films permit a number of interconnect options for parallel optical links depicted in Figures 2 and 3 and described below are:

Interconnect Options for Parallel Links --1

1. Board Edge - on substrate



2. On and off substrate



3. Off substrate



Fig. 2: Pre-processed self supporting flexible links can be configured into diverse link options. Depicted are optical interfaces with MT ferrules and butt coupling, I/O mirror coupling with ball soldered and aligned chips. Generic link configuration examples referencing the numbers used in the text include 1) for board edge and on substrate, 2) for on and off substrate and 3) for completely off substrate but board associated are shown as examples.

Hybrid options including either on- or off-substrate link to I/O mirror and lens arrays for interconnectivity to the underside of a substrate or to an optical layer in-between substrates.

On-substrate or below-substrate surface waveguide arrays bending 90 degrees perpendicularly off board-to-connector ferrule and daughter board that has edge connection ferrules. Using guide bending flexibility within motherboard ferrules enables daughter-board to motherboard interconnection to be flexibly compatible with insertion requirements for electronic connectors also on the daughter board. Lens coupling between motherboard and daughter-board ferrules is being explored to allow for an air gap and alignment tolerance instead of direct zero air gap contact couple. Multiple stacked waveguide film layers at the ferrule interface allow for waveguide array interconnections from daughter-board to daughter-board.

All these interconnection embodiments include a few critical optical interfaces which are for a) waveguides to/from optical fibers or b) waveguides to/from waveguides or c) waveguides from VCSEL's, edge-emitting diode lasers, and/or to photo detector connections. These three basic optical interfaces are in 1 to 3 below and in Figures 2 and 3. The 4th interface below is a fundamental optical guiding interface important for waveguides to./ from graded index fibers.

Out-of-plane I/O (input / output) mirrors that deflect the signals perpendicular to the waveguide film surface that are typically formed at the edge of a waveguide array film. Deflecting mirrors for each waveguide are constructed in the film sheet not at an edge and are being optimized.

Butt coupling where the interface is typically cut perpendicular to both the waveguide film and to the waveguides in the film plane

Waveguide-to-lens array coupling with either 1) or 2) above but with sufficient lens working distance to operate for coupling distances greater than ~ 100 microns.

Optimum coupling between standard graded-index optical fibers requires appropriate compatibility or near match of propagating and transmitting angles (referred to as NA or numerical aperture match). Also the lowest loss coupling to and from these fibers requires a) for transmitter Tx interfaces reduced guide size for waveguide to fiber to couple into the higher fiber core index region at the core center and b) for receiver Rx interfaces guide sizes larger or at least equal to the fiber core size to collect all the fiber-to-waveguide coupled light. Obviously bi-directional coupling requires a compromise on guide dimensions to best optimize the system performance.

To meet specific application requirements, optical functionality can be imaged or incorporated within the parallel link waveguide films with appropriate coupling interfaces and configurations described above. Useful functionality to be shown later in this article, includes crossovers, splitters, couplers, and combiners.

GENERAL DESCRIPTION FOR OPTICAL WAVEGUIDES

Waveguides operationally are “wire like” regions of higher refractive index within a surrounding matrix of slightly lower refractive index. Light propagating within the waveguide remains trapped as long as the glancing angle at the edge of the waveguide is not too great otherwise the light escapes. This phenomenon is similar to how light is trapped or escapes from or enters a swimming pool depending on the angle it impacts the surface. This is why a fish can see you from the bottom when you are just walking up to the creek since as the critical angle is reached for total reflection, light from your image is nearly parallel to the water surface and is refracted down to the fish.

Glass fibers are used for both telecommunication and datacommunication applications and have a higher refractive index core that traps the propagating signals. If the size of the higher index waveguide core is around 6 microns, embedded in 125 microns of lower index glass, light can really travel in or near the core only in one path with only slight angular deviations. Think of a highway tunnel under a mountain or river. For a single lane highway the driver has very little option to swerve as the single path option is confined. In an optical waveguide this is called a single mode (SM) waveguide. Single mode waveguides are used for high data rate telecom signals over long distances as all signals come out at nearly the same time and don't get blurred in time.

Larger core waveguides allow for multiple paths to be taken. Again with the analogy of a multilane highway tunnel, the driver can swerve around back and forth taking many different straight and swerving paths. Thus some travelers will get through the tunnel sooner than others. In optics these multiple allowed angular paths are referred to as multiple modes (MM) that have specific angular values based on constructive and destructive interference of the nearly monochromatic laser light. Viewing the output end of a multimode waveguide that is propagating many different interfering angles or modes is shown for a nominally 50 micron square waveguide in Figure 4. The granular light appearance is evidence of many modes being propagated. For short data communication links the differences in transmission times for these modes do not sufficiently blur the signal's arrival so MM waveguides are used today for shorter <100 meter links even for very high frequency signals.

Other defining factors in optics require that the refractive index from inside the waveguide to the outside be larger to sustain the higher propagating angles in the waveguide. If the core-to-surround index difference is too low, the light

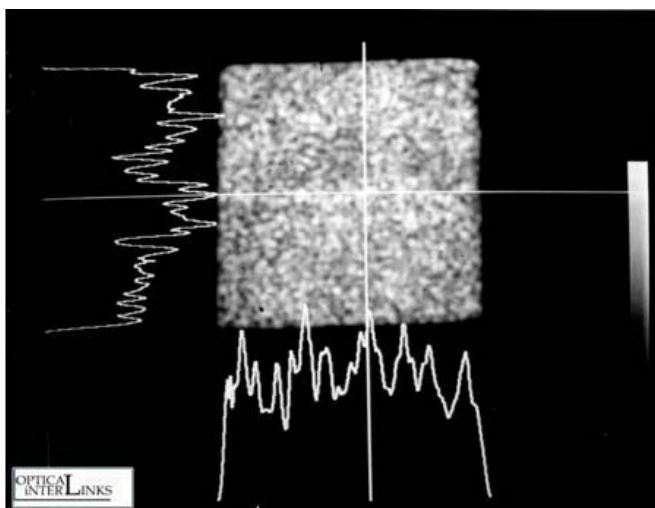


Fig4: Multimode Waveguide Viewed at the Output Film End: is referred to as the near field image. The waveguide shown is approximately 50 x 50 microns with a large number of different allowed propagating angles creating a speckled pattern referred to as modes. The intensity profile is extremely uniform. Read out along the crosshairs in the x and y direction indicates the modal intensity profile

escapes, or conversely if the input angles are too great for a given index difference the light also escapes, sort of like porous tunnel walls.

Summarizing waveguides: SM waveguides are typically about 6 microns in width with a refractive index of approximately 0.006 over the surround sustaining propagation angles of $< \pm 7$ degrees and are primarily used today in telecom applications. MM waveguide cores range from 10 to 100 microns in width/diameter with a refractive index typically of 0.02 to 0.035 over the surround and are primarily used for data communications links and circuit board interconnectivity. This high index difference sustains propagation angles of $< \pm 18$ degrees or so within the guiding core. For low coupling loss the interconnection offset precision for single mode waveguides requires ± 0.5 microns while multimode guides of 40 microns widths requires $< \pm 5$ microns. Thus for substrate-based optical interconnections, MM waveguides are preferred as they are substantially more tolerant of alignment offsets and thus less costly to connect and manufacture.

Other important factors for a useful optical interconnect include low optical absorption and low optical scattering smooth waveguide walls so that sufficient light gets through the link and can couple well between sources and detectors.

Embedded buried waveguides between board substrates

Considerable discussion in the industry relative to creation and application of waveguide optical interconnections has revolved around trying to embed an optical layer during the multi-layer board assembly process. The intent is to require a polymer waveguide film sheet or link to be aligned and placed between two multilayer substrates, like FR4 boards, and be subjected to the high temperature and pressure required to bond all the substrate layers together during the board construction process. The author's perspective is that this will create many adverse issues for embedded polymer waveguides. To maintain the less than 5 micron waveguide alignment offset tolerances required for multimode (MM) waveguides will be a challenge for any polymer system under high temperature and pressure fabrication conditions. These issues include, but are not limited to, thermally induced softening, pressure distortions as well differential thermal expansion during heating and bonding. If a polymer waveguide system survived, to create the precise optical interfaces connecting components with waveguides trapped between two rigid millimeter or even thicker boards would seem to be extremely complex and difficult. Some industry or university groups may have made progress trying to develop this technology approach but that is beyond this article's scope. Finally, what is the manufacturing yield situation if we assume that the technology exists to enable a waveguide system to survive, maintain waveguide array alignment and be effectively interconnected under these adverse pressure and temperature conditions? It would seem that there is still a question as to whether the potential manufacturing yield loss cost would be acceptable, since a process or material failure or alignment problem would necessitate scrapping the entire board structure which could be an expensive loss.

Alternatively, waveguide film sheets could be constructed and inserted with no premachining for connectorization between two already completed substrate boards avoiding the high temperature and pressure. Without the pre machining for connectorization and optical interfaces, manufacturing difficulties for creating and metalizing in-situ mirrors at the base of open vias would be a challenge similar to creating alignment under high temperature/pressure processing above. Alignment between surface components, vias, lenses, mirrors and waveguide structures must have less than 5 microns misalignment offset for acceptable interconnect system performance. The author's believe that these implementation difficulties and costs are beyond the scope for this discussion for practical low cost connectivity.

HISTORICAL COMMENT: Optical glass fibers for telecom applications were first manufactured with sufficiently low loss by the late 1970's to begin test installations. As late as 1985 a multimode optical fiber link on the east coast between Washington and New York was proudly demonstrated to one of the authors and was being used by Bell Atlantic (now Verizon). Shortly thereafter single mode glass optical fiber was sufficiently perfected to be installed with optical losses progressively becoming rapidly lower over the next decade for practical central office and undersea installations. The rest is history as glass optical fiber now brings phone, TV, and internet to the home in many places as well as connecting central offices and spanning all the oceans for telecommunications.

During the mid 1980's it was recognized that short interconnecting links and optical function capability like splitters, combiners etc. would be needed at low cost particularly as the fibers started to move to boards and into computers. Many fiber technology approaches were developed and commercialized to provide splitters, combiners and basic functionality. In addition, considerable effort to develop planar sheets of polymer waveguides was undertaken by laboratories around the world. Polymer waveguides were thought to be the ultimate route for versatility and manufacturability. Considerable efforts continue today with a number of practical applications being implemented today as reviewed in the article. The basic polymer waveguide creation processes are reviewed in the next paragraph.

POLYMER WAVEGUIDE PROCESS TECHNOLOGY

Over the last 20 years there have been many process and material technologies explored to develop planar polymer waveguide containing films capable of producing waveguides that meet perceived and evolving industry requirements. Sorting through the various techniques used to make polymer waveguides, these processes can be lumped into two basic classes, both primarily using photolithographic (and sometimes direct laser writing) waveguide defining exposures. The distinctly different processes for the two classes are:

Ridge Technology: Initially a polymer ridge or conversely a trench is constructed through molding, embossing, or etching of a ridge or backfilled trench with higher refractive index polymer than both underlying and subsequently applied backfill/overcoated polymer. See Figure 5 for a schematic outlining the generic process steps for ridge and trench polymer waveguide formation. This lower refractive index clad surrounding the waveguide region creates the waveguiding properties. The ridge formation approach has been most broadly explored with many variations. Different polymer materials have been evaluated depending on the formation of a ridge (or conversely a trench) that forms the basis of square or rectangular waveguides.

Diffusion Technology: Formation of a high refractive index waveguide as a result of monomer diffusion into the light exposed guide forming region with no mechanical or chemical etching contact. See Figure 6 for a schematic depicting the process steps for this diffusion technique. The technology originated in DuPont as Polyguide™ in 1985 with subsequent development by the inventors (one of the authors) outside of DuPont under the name GuideLink™ at Optical CrossLinks in 1998 and now Optical InterLinks in 2006. Essential process features are the photomask defined light exposure in the waveguide forming region of a mobile monomer in a polymer matrix converting all monomer to polymer. This is followed by continued monomer diffusion into the guide imaged region from the surround that increases the density. Subsequent addition of other laminated monomer/polymer diffusing layers with the entire typically three or more layer configuration completely photopolymerized after diffusion is complete. The essential steps include a light induced imaging reaction, total polymerization light fixing for the entire film, and final bake cure, all using precoated dry materials without waveguide side wall contact. Light and molecular diffusion determine the guide walls.

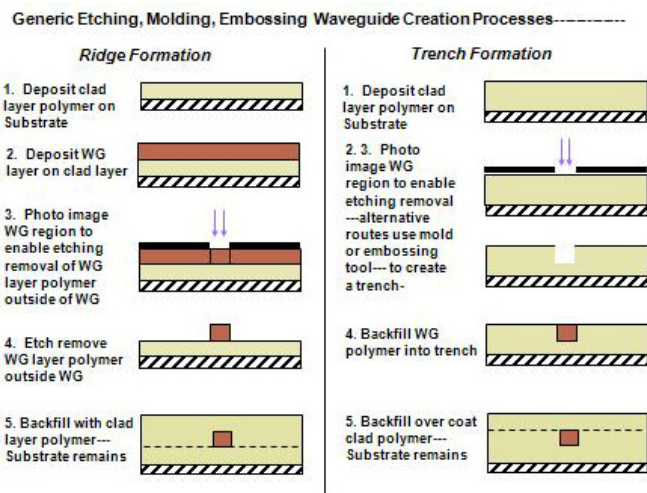


Fig. 5: Generic Etching, Molding, Embossing Waveguide Creation Processes: Both ridge and trench formation options are illustrated. Polymers can be imaged using photo resists to create the patterns for selective etching or photopolymers can be used for negative or positive etching

OPTICAL INTERLINKS GuideLink™ Waveguide Process --- all layers are Monomer + Polymer Formulations pre-coated on Mylar

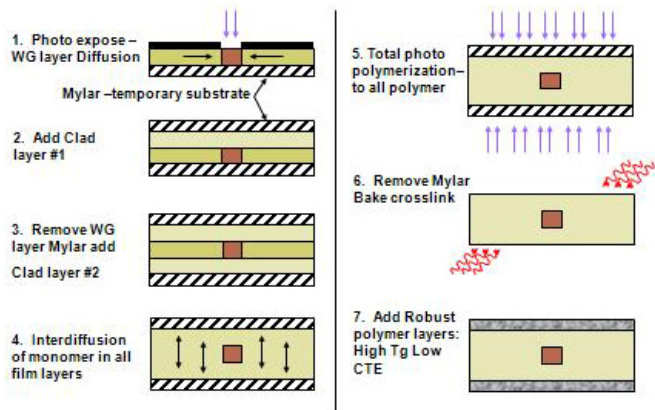


Fig. 6: GuideLink™ formulations are made with a proprietary mix of monomers and polymers. The formulations are optimized to allow for rapid diffusion of monomers into exposed regions enabling light induced self developing of waveguides. This is achieved without direct contact via molds, embossing tools, or etching chemicals/processes. The diffusion process created waveguides have extremely smooth side walls that are defined by the photomask and molecular diffusion. The temporary substrate for used for film coating is all discarded during the waveguide process. Pre-and post-coating shelf life is greater than a year. This lifetime enables pre-QC'd films for desired performance and precise thickness to be created and stockpiled for manufacturing uniformity

The essential steps include a light induced imaging reaction, total polymerization light fixing for the entire film, and final bake cure, all using precoated dry materials without waveguide side wall contact. Light and molecular diffusion determine the guide walls.

A number of different industrial groups and laboratories have been exploring the ridge formation style technique with only a few identified in Figure 7 (next page) who participated in an iNEMI study headed up by one of the authors, Jack Fisher, on optical back-plane technologies. Under Jack's direction an iNEMI subgroup for the effort chaired by the other author, Bruce Booth, developed a polymer waveguide technology attribute table with over 15 participating groups. The figure shown here was the header for the lengthy attribute table. It denotes the two polymer technique classes with representative practitioners from the subgroup. As is evident, only Optical InterLinks is currently involved in developing and manufacturing custom applications using the diffusion technique as proprietary materials, processes and trade secrets are involved. Both ridge and diffusion technologies have the capability to create self supporting waveguide films amenable to pre- micromachining processing to provide fully connectable configurations ready for installation. The process techniques can also create

waveguide films directly on the final application substrate if more appropriate. A number of unique performance and waveguide configuration differences are inherent between the diffusion and/or ridge guide forming processes.

iNEMI – Polymer Waveguide Subgroup

Polymer waveguide process technology:

	Technology based on: <u>Monomer Diffusion with clad lamination</u>	Technologies based on: <u>Ridge Formation with Clad Backfill</u>		
Technology-General Attributes	Polymerization induced monomer diffusion self development –[3]	Image and develop with aqueous , etching (wet chemical or RIE) , laser direct write	Screen print, molding	Embossing
Practitioners	Optical InterLinks,	Rohm&Haas, IBM,	Genfire / Dow Corning	OptoFoil-Fraunhofer Institute, IZM

Fig. 7: **Polymer Waveguide Process Technology Summary:** The header for a large polymer waveguide attribute table developed during an iNEMI study noted in the text. Practitioners that participated in the study are noted

Since the purpose of this paper is to describe practical optoelectronic substrate interconnectivity, no further direct discussion of the specific technique details will be provided. GuideLink™ diffusion technique attributes germane for optoelectronic substrate connectivity will be evident from the description of how the needs for practical optical interconnections are being met at this point in time.

STATUS FOR PRACTICAL LINK INTERCONNECTIONS

Practical link configurations for optoelectronic substrate interconnectivity have been identified. They primarily involve connectivity options for parallel and functional links. Most noted have been reduced to practice by Optical InterLinks, some are being prototyped with pilot manufacturing, and delivered for real applications. These critical system building-block embodiments for practical applications are described below to identify and elaborate on the key system attributes. Self-supporting waveguide films are used as the starting point. The basic features are demonstrated to confirm practical connectivity is achievable and at least most are available for applications.

CONNECTIVITY ISSUES AND OPTICAL INTERCONNECTS

All the optical interconnection links as described previously include the basic coupling capabilities noted below These coupling capabilities are all demonstrated by the prototype products shown in the figures. Critical connectivity issues for practical applications are noted for each.

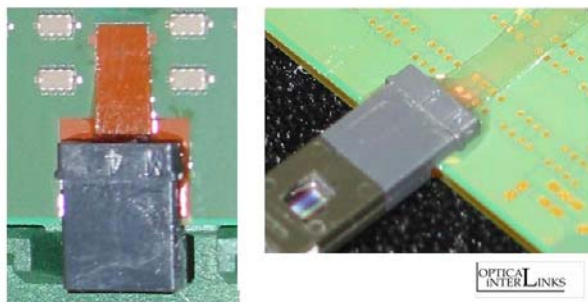


Fig. 8: **Board Edge Connectivity using MT Style Ferrules:** Waveguide films are precisely cut to align the up to 12 waveguides with less than +/- 5 micron offset relative to centering within the MT ferrule pins. This centering between pins allows for coupling to standard MT connectorized optical fiber arrays and / or waveguides at the conventional 250 micron center to center spacing. For waveguide to waveguide coupling center to center spacing can be for example as small as on 50 micron centers for 40 micron MM guides. All ferrules are pre assembled to the waveguides and QC'd before installation. ted

Substrate edge ferrules with similarly precise aligned waveguides using butt coupling interfaces. Butt coupling (surfaces cut perpendicular to waveguide or fiber axis) can be coupled to fiber arrays or to polymer waveguide arrays held in similar ferrules.

Figure 8 shows board edge ferrules to align 12 waveguides to 12 optical fibers through MT style ferrule connectivity.

Critical connectivity issues are:

- ensuring no waveguide loss producing microbends where the film leaves the board edge going into the modified MT ferrule for the connector interface,
- optimizing performance to match fiber and waveguide allowed propagating angles (referred to as numerical aperture or NA and defined as the sine of the half angle of the radiated Gaussian light pattern at the

5% intensity points) and waveguide dimensions taking into account the graded index profiles of fibers versus the step profile in polymer waveguides,

- ensuring matched center to center spacing (pitch) and allowed max offsets are not exceeded to assure good coupling,
- using micro ferrules designed for small array coupling footprints (see 3) below) although for these, board-edge connection machined slots for alignment pins are required, and
- for coupling to and from polymer waveguide arrays on a board, very high densities in the several hundred interconnections can be achieved using stacked waveguide films and pitch that is far less than the 250 micron constraint necessary for standard optical fibers.

I/O mirrors cut at 45 degrees to deflect waveguided light perpendicularly from one or more waveguide films in or out of the guides and to/from sources or detectors components. An example a waveguide deflecting metalized mirror is shown in Figure 9. Typically the unguided light path distances involved are ~50 microns. The mirror surfaces are usually

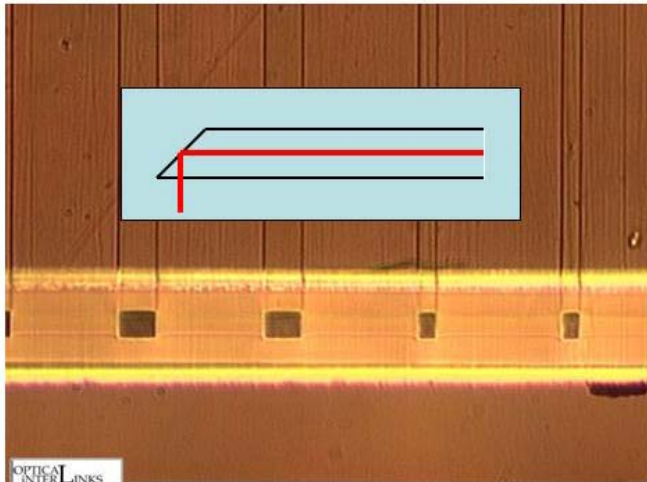


Fig. 9: Metalized Mirror Reflected Waveguide Image for Transmitter and Receiver Coupling: The view of the actual waveguide reflected patterns is looking up from the underside into the schematic thru the flat surface. The nominal ~25 micron wide guide is designed to efficiently couple light into the high index center of graded index optical fiber. The wider ~ 60 micron guides can more efficiently collect the light from the fiber in the receiving mode

metallized to ensure that high angle multimode propagated light is reflected (and not passed through a total internal reflection (TIR) mirror without metallization. Propagating angles with reasonable mode fill are likely to exceed the total internal reflection critical angle allowed. Applications include substrate attached guides for flip-chip access, access to overlying components or top-access configurations as used with flexible jumpers and functional devices not substrate attached . These mirrors can be cut at 45 degrees by microtome (thin blade used in tissue cutting) or excimer laser on the film edge. For mirrors in the center of waveguide film sheets, excimer laser micromachining will be used to create an “in-situ” mirror when required.

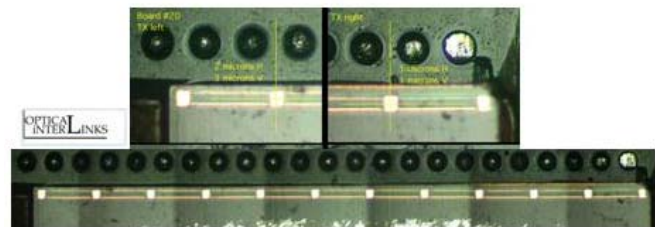
Precision alignment on substrates of the waveguide film arrays for reflected light coupling is critical and is achieved by first precision cutting to locate the waveguides in the film strip for substrate installation. A 12 guide array is shown precisely aligned to flip chip locating solder balls in Figure 10. Since alignment for each guide is critical and here is within +/- 3 microns for the example shown, the run out or accumulated position

error must also be similar as noted.

Critical connectivity issues are:

- Alignment offsets including runout over the entire waveguide array must be confirmed to match the part requirements before assembly. Runout/offset for vertical and horizontal waveguide positions relative to solder balls must be within system allowed tolerance for flip-chip component attachment.
- Assembly operations must be completed carefully to prevent damage that can compromise waveguide and mirror performance. The waveguide film must fit with uniform and minimum air gap under the flip chip components.
- Alignment and waveguide performance must be maintained when subjected to IR solder reflow used for flip chip attachment. Typical max conditions for IR reflow are 300C at less than a minute. Stability of waveguide films and optical properties is required for sustained times at temperatures up to 125C.

Fig. 10: Substrate Attached Waveguide Array Alignment: Twelve waveguides on 250 micron spacing are aligned precisely to solder balls on a substrate for subsequent flip chip bonding of VCSELs (vertical cavity surface emitting lasers) or PD's (photo detectors). Magnified image of the two end guides with offset accuracy within 3 microns is shown with run out spacing for the guides similarly controlled



Guides are positioned 146 microns below solder balls, maximum runout for all 12 guides is 3 microns.

I/O mirror coupling to and from an array of lenses demonstrates the application for a flexible self-supporting waveguide link bridging between fiber ribbon arrays through a mirror with a lens through-board interconnection. An example waveguide sub-assembly is shown in Figure 11 along with a side view schematic showing the installation configuration. Lenses are needed for greater than the usual short ~50 micron distance. With lenses, unguided distances can be several hundred microns to greater than 1mm. Lenses facilitate imaging of component I/O with the waveguides through the mirror. This lens waveguide array system requires a number of precise alignment shims to span the distance and precisely couple to and from the waveguides. Applications can include traversing between top and bottom substrate surfaces or through boards to connect sources and detectors to the waveguide arrays.

Critical connectivity issues are:

- Alignment for waveguides, lens elements and

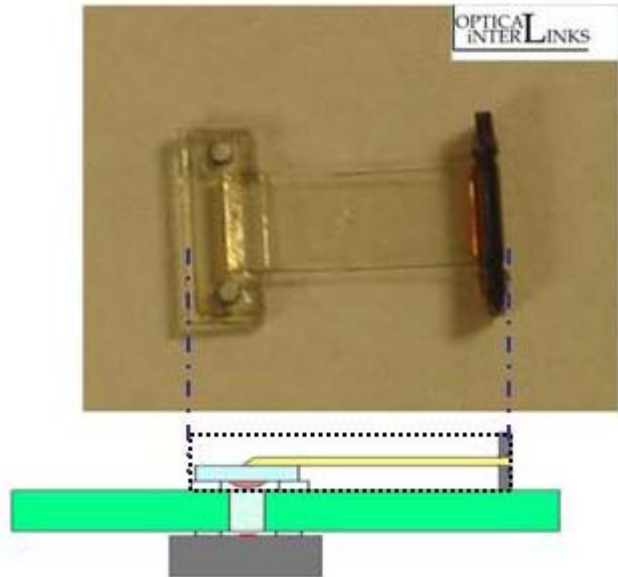


Fig. 11: Waveguide Sub-assembly for Coupling between Lens Array Imaged Components and Fibers thru a Micro-ferrule: The side view schematic cross section depicts the sub-assembly part and how it is aligned to the chip placed on the substrate undersurface. Optical loss for the sub-assembly is typically less than 1dB thru the fiber connecting interface to the lens array output operating at 850nm. System loss is well within specifications. The waveguide link remains off substrate as a flex link with stability demonstrated for many hours at 125C.

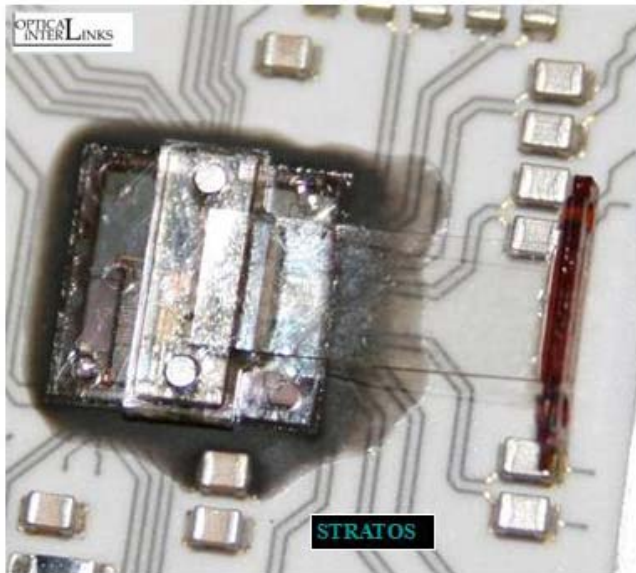


Fig. 12: Transmitter / Receiver (Tx/Rx) Waveguide Subassembly Mounted on the Applications Micro Circuit Chip. Final configuration for the transmitter / receiver (Tx/Rx) optical interconnected link mounted on the circuit substrate as described in Figure 11 is shown. There are over 10 specially design aligning parts with the waveguide array containing 4 Rx and 4 Tx waveguide links precisely oriented for coupling to a fiber

- Alignment specs and tolerances noted for edge connections and mirrors are identical for this interconnect embodiment including having transmitter (Tx) and receiver (Rx) optimum-sized waveguides for high performance coupling to graded index fibers as is also shown in Figure 9 where the 60 micron wide guides are for the receiver and the 30 micron wide guides for the transmitter link. For other applications the guide can be varied as well.

Board-to-board coupling for perpendicular connected substrates as for mother to daughter boards is achieved with ferrules in latchable housings using butt coupling multilayer arrays of waveguides.

components must be within a few microns to ensure low loss connectivity.

- Optical fiber to waveguide array interface is achieved with an MT-like ferrule or micro ferrule for the example shown, which is not substrate attached and is thus a flexible link as it bridges to the outside of the package.
- The entire packaged unit on the ceramic substrate shown in Figure 12 with fiber ribbon has achieved stability over many hours at 125C a typical operating range max.
- Waveguide assembly including fiber interface, mirrors, and lens unit has a system loss of less than 1dB (20%) and the entire package system loss is within operational specs that includes coupling from the 4 VCSEL 's thru the system and vice versa back to 4 detectors. The final Stratos Optical Technologies TxRx unit without the package cover is shown in Figure 13.

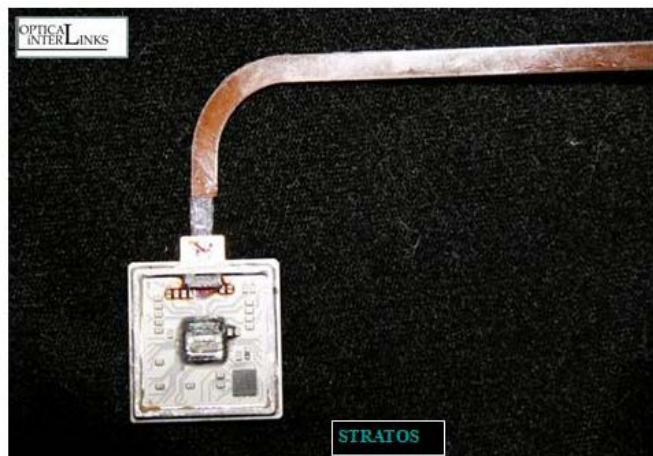


Fig. 13: Final Package for Tx and Rx with Fiber Flex Array Interconnection: MT fiber array ferrule is connected permanently to the waveguide array micro ferrule. After final system performance tweaking the package lid is hermetically bonded to the top and completed by Stratos Optical Technologies for their transceiver package

CRITICAL CONNECTIVITY ISSUES ARE:

- All the alignment and precision issues brought out in 1 above for MT ferrule style connectivity are relevant.

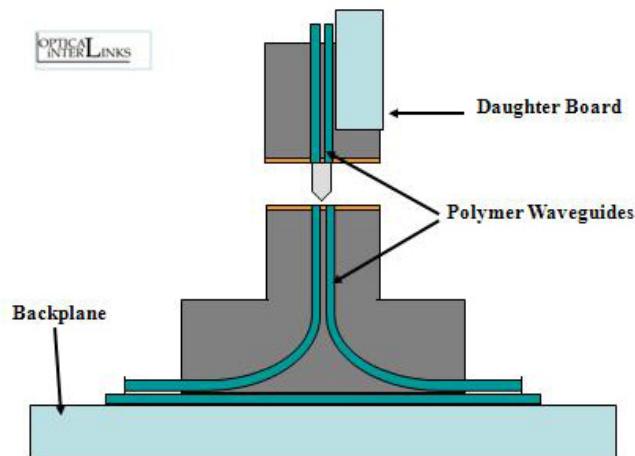


Fig. 14: Schematic for Daughter Board to Backplane/Mother Board 90 degree connectivity: Board edge connectors as noted previously for the daughter board butt couple thru MT ferrule designs to waveguides that are bent thru 90 degrees up from the backplane. Radius of curvatures (ROC) of 5 mm are used with no increase in optical loss. This concept facilitates waveguides going from board to board along the backplane or under the daughter board junction as well.

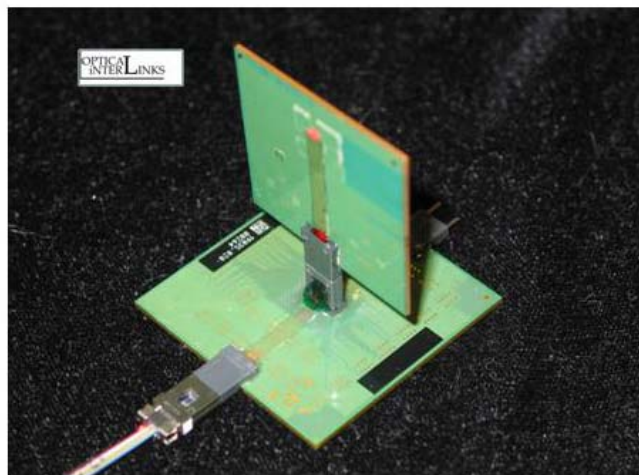


Fig 15: Board to Board Interconnection Concept Configured as described in Figure 14: Reduction to practice demonstration for the 90 degree connector system showing interconnected boards. A 12 over 12 waveguide MT ferrule interface is used. Projected losses for the system are between 0.5 to 1dB.

- Balancing daughter board insertion forces with latching between electronic and optical connections that require a zero air gap are challenging and important to achieve for low loss connections with multiple insertion capability. Capitalizing on the bend flex capability inherent with GuideLink™ waveguide films enables the required flex as the daughter board is inserted. These waveguide films have undergone over 4000 bend operations at a one mm ROC so a simple 4mm ROC, that is used for the 90 degree bend, is also depended on for bend/flex during board insertion in the connector. GuideLink™ bending is well within the capability required. In addition, the bending capability has opened opportunities for through the hinge connectivity for cell phones and lap top computers.
- Alternative techniques using a lens-to-lens coupling at the daughter board-to-backplane optical interface allow an air gap for potentially more forgiving positioning.

Particular emphasis is aimed at polymer waveguide-to-waveguide interconnection thru the daughter board edge to backplane/mother board guide as depicted in Figure 14 with examples in Figure 15 and 16. To achieve daughter board-to-daughter board connectivity along the backplane precisely arranged stacked guides and very high density arrays are likely to be required. Direct zero air gap contact is desirable for the ferrule to ferrule interface. Spring-loaded compression combined with initial insertion flex latching is required for the connection similar to the latchable MPO or MPX style connector housings that are commercially available. A conceptual schematic for this housing is shown in Figure 17 (next page).

- Balancing daughter board insertion forces with latching between electronic and optical connections that require a zero air gap are challenging and important to achieve for low loss connections with multiple insertion capability. Capitalizing on the bend flex capability inherent with GuideLink™ waveguide films enables the required flex as the daughter board is inserted. These waveguide films have undergone over 4000 bend operations at a one mm ROC so a simple 4mm ROC, that is used for the 90 degree bend, is also depended on for bend/flex during board insertion in the connector. Guide-Link™ bending is well within the capability required. In addition, the bending capability has opened opportunities for through the hinge connectivity for cell phones and lap top computers.

- Alternative techniques using a lens-to-lens coupling at the daughter board-to-backplane optical interface allow an air gap for potentially more forgiving positioning. The approach would likely eliminate the need for a flexible waveguide. Lens routes have been explored by others and will be evaluated with a collaborating company for comparison to the zero air gap flexible film option above.

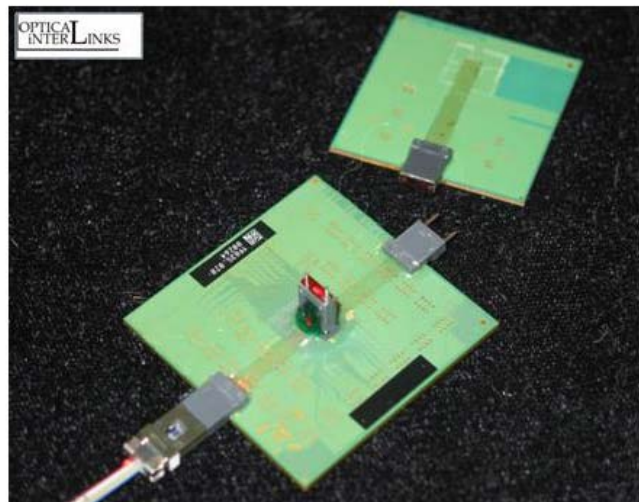


Fig 16: Board to Board Interconnection Concept as in Figure 15. Boards are separated for the demo.

tioning. The approach would likely eliminate the need for a flexible waveguide. Lens routes have been explored by others and will be evaluated with a collaborating company for comparison to the zero air gap flexible film option above.

- Butt coupling of stacked waveguide arrays for the D board to BP connector interface requires both vertical and horizontal precise centering and runout control to within a few microns for both connectors. Two and four-layer arrays have been successfully created in large numbers for 4x12 and 2x12 interfaces to detectors and VCSEL's/PD's for Tx and Rx systems. A 4x12 array interconnection RxTx unit built for Teraconnect is shown in Figure 18.

Waveguide film edge ferrule coupling with self-supporting links and/or stand alone functional devices. Arrays of single or multi-layer waveguides are precisely centered or positioned within the ferrule as required. Figure 19 shows an assortment of MT ferrule connected flex jumpers and board edge substrate

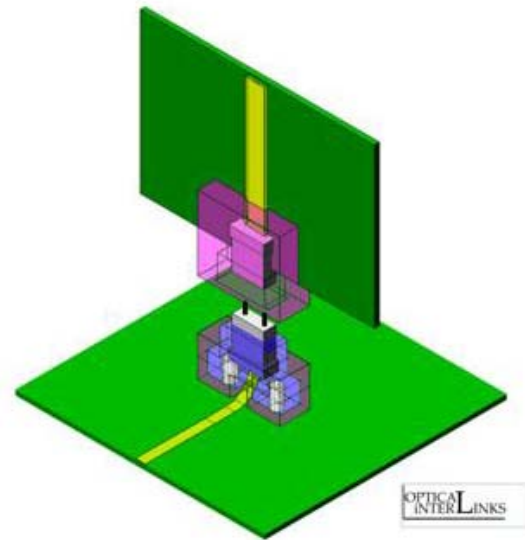


Fig 17: Final Configuration Schematic for Flexible Positioning Housing: As described in the text the interconnecting ferrules must latch and then float in position identical to commercial MPO style connectors to avoid a hard bottoming yet insure a zero air gap optical connection when a daughter board with electronic and optical interfaces are inserted.



Fig 18: Stacked Waveguide Array Interface Coupling: A four by twelve stacked waveguide array with 125 micron center to center spacing vertically and horizontally is shown. The array is created from 4 waveguide films with imaged guides creating the 90 degree bend in the 4 film array on the left. Each of the 4 waveguide array films contains 12 precisely located operating waveguides. Two films are stacked and connected to a 12 over 12 MT connector ferrule with spacing optimum for the same 12 over 12 fiber coupling. The guides were within +/- 5 micron centering individually and with run out. The final package with the wishbone shaped waveguide assembly to interface to the components were all developed and beta tested by Teraconnect for high data rate transceiver before market conditions terminated the effort.

described for the above.

Backplane/motherboard waveguide array interconnects have been created with highdensity waveguide arrays in a 40 cm long backplane demo interconnecting two daughter boards. The 47 cm waveguide optical path including 7 cm for the daughter boards had multiple connections operated within the loss budget of 15dB. The flex circuit shown in Figure 1 with the waveguide top and end view shown in Figure 20 (next page)was substrate attached for the board demo in Figure 21(next page).

Other interconnection variations for direct fiber or waveguide attachment schemes such as for novel butt-couple configurations between waveguides and semiconductor laser sources have been reduced to practice but are not described in detail here. Practical connectivity is achievable through the versatility provided by using self-supporting precisely machined stable film structures thus enabling an extensive range of application options.

links fully QC'd and ready for installation. Critical connectivity issues are:

- Alignment, precision, and coupling issues are as

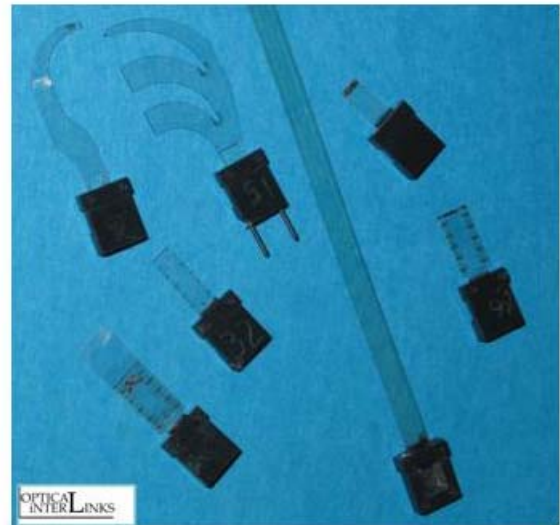


Fig. 19: Collection of Connectorized Optical Links: Creation of a diverse array of optical links for flex circuits for on or off board applications is important to facilitate practical connectivity. The units on the top left were designed to go from the board edge around to the side of surface mounted components with several separated interfaces on the chip.

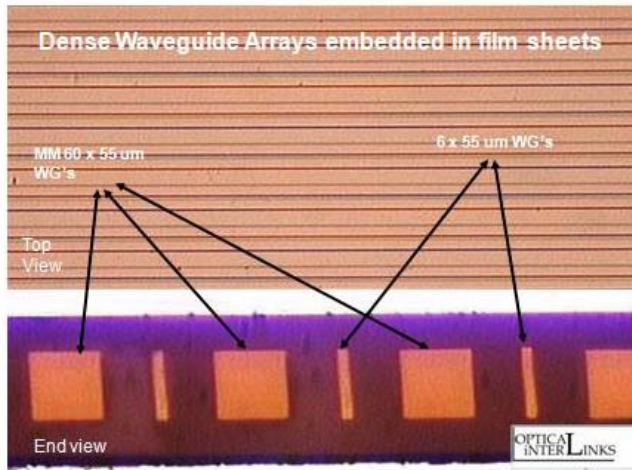


Fig 20: Dense Waveguide Array Link: The top view is of a dense 125 micron spaced waveguide array and the bottom view is the film edge on image of the alternating 55 micron wide and 6 micron wide waveguides. The ability to construct smooth parallel wall guides with the GuideLink™ process is evident from the figure.

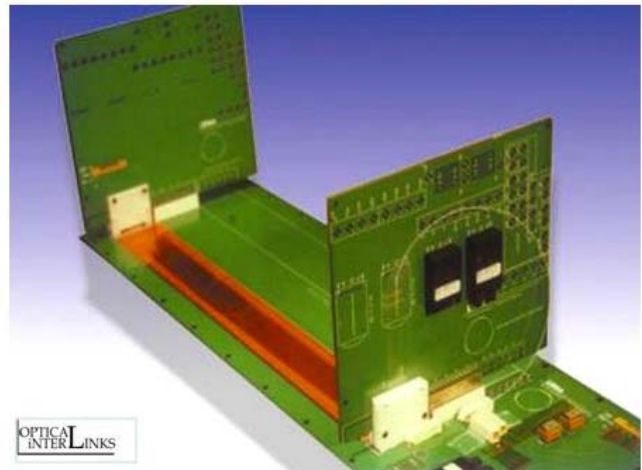


Fig 21: Waveguide Arrays Configured for Long Backplane Circuit Board Runs: Waveguides in long film strips were imaged, connectorized and placed on simulated backplane runs for a capability demonstration for Litton Interconnects. The total loss budget was within the 15 dB limit specified at the time and included two daughter board interconnections and a splice to connect the 40 cm board run length.

Functional interconnectivity, in addition to parallel links for distributing signals, is used for the distribution and or combining of signals with increasing interest for substrate based connectivity as well as for stand alone devices. High resolution imaging and processing capability is required to create these planar polymer waveguide splitting, combining, multi-input-to-multi-output distribution star couplers, and multiple re-routing capability for parallel links through crossovers. The waveguide configuration at the splitting point where waveguides come together or separate must be as sharply defined as possible to avoid scattering light as it splits, combines, or is separated into multiple waveguides. The self-development GuideLink™ technology enables these junctions to taper to a fine point as is shown for several functional configurations. Figure 22 shows the tree branch splitter with a magnified sharply defined split junction and its final packaging in Figure 23 where we spliced the 16 outputs to fit as an 8 over 8 output into a standard MT ferrule. MT ferrules at standard fiber 250 micron spacing can only fit 12 guide channels in a single row. An 8 to 1 combiner for 8 different wavelengths and one fiber coupled output made for OptiComp is shown in Figure 24 (next page) with a magnified insert

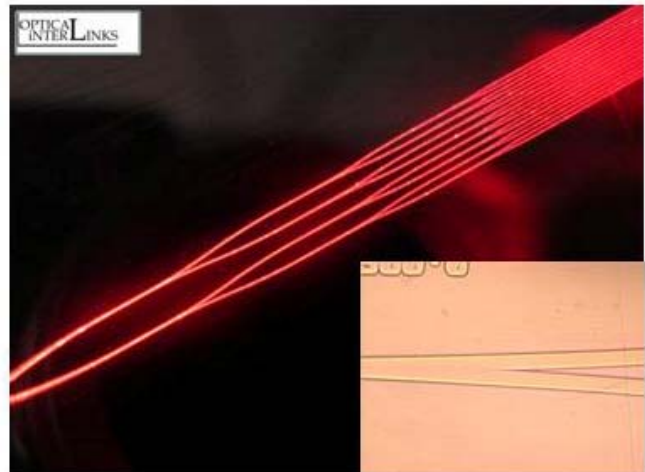


Fig 22: Tree Branch 1 to 16 Splitter Design: One to sixteen splitters with 1.8 dB excess have been connectorized and packaged as shown in this and the next figure. A magnified splitter junction is shown demonstrating the extremely sharp junction or apex where the guides separate. This sharp junction enables extremely low loss splitters with good balance performance within +/- 0.5 dB. Since the GuideLink™ imaging process uses monomer diffusion to create the waveguide patterns and does not rely on polymer removal or backfill very sharp low loss junctions can be created

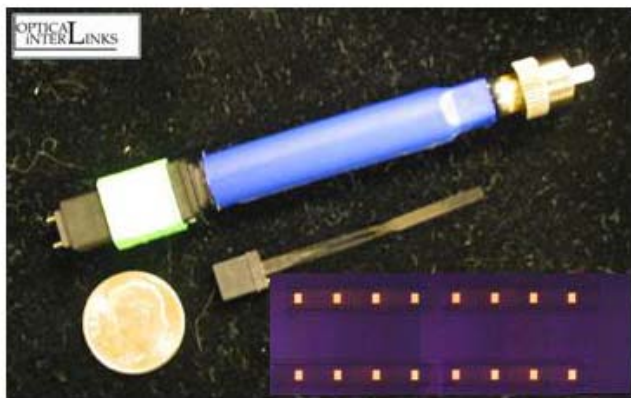


Fig 23: Packaged Tree Branch 1 to 16 Splitters: MT ferrules have space for only 12 optical channels on 250 micron centers between the fixed pin spacing of 4.6 mm. To connectorize the 16 outputs compatible with standard fiber spacing the GuideLink™ splitter is partially cut into two outputs of 8 and folded over to create an 8 over 8 configuration. The outputs and the final MT/SC package in shown in the figure. The excess loss was 1.8 dB +/- 0.5 dB.

shown the sharply defined 8 combining and splitting junctions as the light enters and leaves the mixing region. The completed packaged unit is shown in Figure 25 (next page) with inclusion into Opti-Comp's circuit board.

To create these sharply-defined regions using other guide forming processes would seem to be very difficult to achieve. For these techniques the polymer has to be removed and/or backfilled without leaving bubbles or voids that scatter light between sharply-defined smooth walled joining/splitting waveguides. Formation of these high-resolution structures using the GuideLink™ self-development diffusion processes is as routine as exposing straight parallel link arrays.

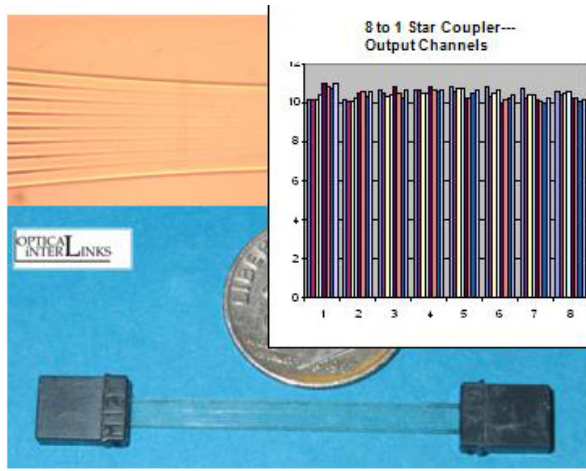


Fig. 24: Star Couplers for Broad Signal Distribution An 8 x 8 star coupler is shown with excellent balance within +/-0.5 dB and low excess insertion loss of ~ 1.4 db. The data for each of 8 inputs is shown with the 8 balanced outputs. A magnified image of the 8 input and/or 8 output regions shows the excellent sharp waveguide splitting and combing resolution achievable with the GuideLink™ technology. The capability enables a family of star coupler with n inputs and m outputs with designs concepts for compact connectorized units up to 24. In addition, splitters can be configured with any desired output avoiding the constraints in numbers inherent with tree branch systems.

8 to 1 Multimode Combiner
Optical InterLinks



WDM Transmitter Modules
OptiComp Corporation



Fig. 25: Novel Waveguide Designs for an 8 to 1 Combiner An 8 to 1 combiner was created using small width input waveguides with optimized waveguide designs. The unique design combines all inputs with good coupling and low excess loss of around ~2 dB coupling into a single optical fiber. OptiComp Corporation installed multi-wavelength combiner on their board transmitter unit shown in the figure. The waveguide design also operates as a splitter with ~1dB excess loss for the receiver side of the circuit.

To achieve extremely low loss crossovers to re-order parallel links, photo image created low refractive index unexposed regions inside the multimode waveguides are created that enable actual waveguiding in the crossing region as opposed to no waveguiding which is standard other waveguides. Thus with the low index regions defining the light path thru the crossover light is not scattered out of the guide while traversing the unguided area where the other guide is crossing. Figure 26 shows both the unguided and guiding crossovers with these features. These small low index waveguide feature capabilities enable extremely dense close spaced guide arrays and are also expected to be exploited for other applications such as novel optical sensor read heads.

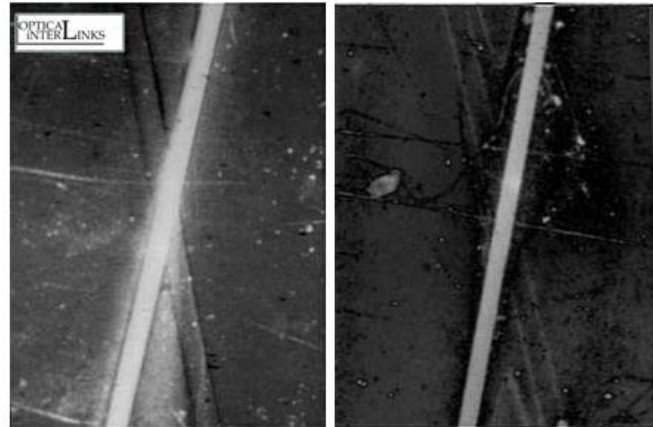


Fig. 26: Low Loss Waveguide Crossovers for Re-arranging Parallel Links On the left are two crossing multimode waveguides constructed with standard intersecting waveguide designs. Propagating light in the intersecting region remains unguided and thus diverges and leaks out creating a high optical loss. On the right is waveguide using GuideLink's™ capability to image low index 4 micron wide regions inside the multimode waveguide. As depicted the approach enables guiding within the intersecting region and extremely low loss in the <0.01dB per cross over.

Critical connectivity issues are:

- For functional interconnectivity within planar waveguide links on substrates or as flex jumpers, the devices can be embedded within the link so that connectivity would be identical as the parallel link configurations with MT's, mirrors etc. above.
- For functional interconnectivity as stand-alone units connectivity can be achieved with similar MT style ferrules with the same constraints and tolerances for pitch and runout and for NA and guide size when interfacing with fiber arrays. For single inputs simplified fiber alignment and support structure are created to robustly lock the single fiber to the waveguide. For example the stand alone 8 to1 combiner in Figure 25 had tapered waveguides with good coupling to single fiber. The form factor for these devices is small and compact with excellent performance for excess loss and good balance.

These functional configurations demonstrate practicality for a number of stand alone or substrate attached applications that are realizable today.

SYSTEM ISSUES ---What is needed for an interconnection system to be considered practical and sufficiently developed or mature to warrant application and deployment in real world systems?

Thus far this article has reviewed and discussed:

- 1) The generic capabilities and requirements for practical OE substrate connectivity,
- 2) Polymer waveguides and the processes for creating and using them as a leading candidate of choice for daughter board OE component connections,
- 3) Connectivity application options and examples for reducing them to practice with associated connectivity issues that need to be considered along with potential for functionality.

To facilitate practicality, design engineers must address the entire OE substrate connectivity system's requirements including; performance, lifetime / survivability / reliability, and cost issues making trade offs for each specific application depending on whether low end consumer or high end performance is required. These system design items involve:

System attributes to satisfy the current performance requirements. Do the resulting optical electronic interconnections meet all the system performance requirements including links, functionality and loss and are they competitive with alternative technologies? Significantly different performance trade offs exist between for example low end consumer, reliable high volume low cost automotive, and high-end military or space related applications that must be addressed by system designers. Much of the discussion above attempts to address performance and design option topics.

System attributes over time—survivability / reliability / lifetime. Does or can the optoelectronic system continue to meet performance requirements over the anticipated service lifetime for the particular application? The application specific variables to be considered are extensive. For example, some important items are operational conditions such as temperature cycling and max/min limits, vibration, solvents, environmental tolerance issues like dirt, moisture, lifetime aging/ stability (Arrhenius plot projections for loss increases over time at temperature), consideration of relative CTE variations within the system, optical power limits vs. the application, effective polymer Tg versus packaging, RAD hardness against anticipate levels to be encountered, etc. and even standards compatibility.

Systems partitioning is an important architecture consideration for design tradeoffs that is often facilitated by photonic interconnections. Physically separating system segments can in some instances enable distributed architectures that would not be possible electronically. The net effect can be to preserve or enhance system bandwidth and reduce power drain. Sub-system interfaces can be designed more predictably enabling diverse vendors' products to be implemented in the system. Optically multicasting signals opens the door to system designs whose performance can be scaled without changing system architecture. Optical interconnectivity enables partitioning and thus provides system design freedoms enhancing performance.

GuideLink™ optical waveguide interconnectivity provides an example of versatile configuration options as we have discussed. It achieves thermal/mechanical stability and reliability by using robust external packaging layers on both sides of the waveguide structure. These layers provide an effective high Tg and low CTE encapsulation for a completely stable low-loss coupled and self-supporting waveguide film structure operating over the required temperature ranges. A practical system such as GuideLink™ has undergone many evaluations and is continually challenged for each new application, as are all other waveguide technologies, to make sure reliability is sufficient for the specific end use application. A full discussion of this topic is beyond the scope of this article, although reliability requirements have been mentioned throughout.

Manufacturability and costs for the entire system application. Can the system be manufactured cost effectively, reproducibly, and be functional and cost competitive with alternatives? Important processing time and costs include material processing, filtration, and purifications. It is important to ensure adequate lifetime when the polymer mix is not yet coated and when pre-coated on final or temporary substrates before exposure. Pre-exposure shelflife stability is important so that sufficient fully prepared, reproducibly performing and QC'd materials are available to support volume manufacture.

GuideLink™ monomers/polymers both before coating and after coating have a useful shelf life of more than one year prior to actual waveguide exposure. Long shelf life is most enabling for large scale manufacturing operations where a source of reliable unexposed material is essential. Coatings are made on temporary Mylar substrates. For volume applications the coated Mylar films are rolled up with protective cover sheets. Films can have widths over a foot and lengths over 250 feet. The capability to produce precise and reproducible film thicknesses is important for all applications. GuideLink™ multimode coatings using laboratory facilities are coated to within a few microns at 20 to 100 micron overall thicknesses required for the various waveguide applications and coupling interfaces. After coating and exposure the final process step for GuideLink™ technology processing will require for high volume production an efficient operation to complete total photo polymerization exposure and final bake and crosslink/cure. A conceptual design for a reel to reel process that could be altered to a step and repeat process shown in Figure 27 (next page) is suggestive of how high volume manufacture could be achieved. Equipment has been designed and demonstrated elsewhere for related polymer processing using exposure chambers and scroll ovens for final cure to maintain high throughput. Once imaged and fully crosslink/cured, GuideLink™ waveguide films have continued to perform according to specifications even after 16 years under normal lab conditions.

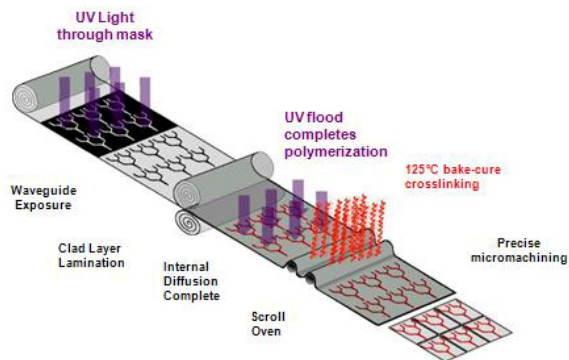


Fig. 27: Continuous to Step and Repeat Waveguide Manufacturing A conceptual process is shown for imaging, adding clad layer by lamination, polymerizing and crosslinking Guide-Link waveguides. This conceptual process provides a practical route for how mass production of polymer waveguides can be achieved with low cost and high volume production that will be ultimately needed for scale up.



Fig. 28: Pilot Manufacturing Assembly Scale up for assembling TxRx parts has begun to increase production and reduce costs with staged workstations for the waveguide lens to substrate transmitter and receiver described in figures 11 thru 13.

Can the entire process be amenable to scale up cost effectively? Waveguide process technology is readily amenable to producing over a hundred square feet of waveguide imaged films per 8 hour shift. Precision machining and assembly are the dominate costs in the current pilot and prototype development stage. Reducing these costs in manufacturing scale up is now being addressed. Development and operation of small scale pilot manufacturing shown in Figure 28 is underway for the Stratos Optical Technologies TxRx packaged link described previously.

The approach discussed in this article where the value of QC'd waveguides fully processed for connectorization before installation saves time, adds versatility and reduces potential yield loss as was discussed, resulting in an opportunity for a minimum cost high performance product. All final assembly variables must be considered including OE system assembly, IR solder reflow, cleaning solvents etc. with QC along every step of the way. Finally the ultimate bottom line is the cost acceptable for the completed system for the applications intended?

Summary

Optoelectronic substrate connectivity is sufficiently advanced, practical and available today to be considered for near term applications. For many in the industry the maturity of optical interconnectivity at the substrate level is sufficient to begin initial prototyping. Technologies continue to be developed and improved that will open up new application opportunities. We believe that approaches exemplified in this article suggest that the route to create self supporting polymer waveguide structures is extremely enabling and cost effective for many applications.

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