

Polyguide(tm) Polymeric Technology for Optical Interconnect Circuits and Components

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ABSTRACT

The expanding information revolution has been made possible by the development of optical communication technology. To meet the escalating demand for information transmitted and processed at high data rates and the need to circumvent the growing electronic circuit bottlenecks, mass deployment of not only optical fiber networks but manufacturable optical interconnect circuits, components and connectors for interfacing fibers and electronics that meet economic and performance constraints are absolutely necessary. Polymeric waveguide optical interconnections are considered increasingly important to meet these market needs. DuPont's Polyguide(tm) polymeric integrated optic channel waveguide system is thought by many to have considerable potential for a broad range of passive optical interconnect applications. In this paper the recent advances, status, and unique attributes of the technology are reviewed. Product and technology developments currently in progress including POLO (Parallel Optical Link Organization) and POINT (Polymer Optical Interconnect Technology) developments funded by DARPA are used as examples to describe Polyguide(tm) breadth and potential for manufacture and deployment of optical interconnection products for single and multimode telecom and datacom waveguide applications.

Keywords : polymer waveguides, optical interconnects, polymer components, optical components, optical connectors, optical data links

INTRODUCTION

The burgeoning communication and information revolution is becoming increasingly ubiquitous impacting every aspect of human endeavor. Unlimited information access is pervasive and apparently culturally irreversible as indicated by the explosive growth of the Internet and the World-Wide Web.¹ It is manifested by higher data rates, more bandwidth, higher density circuitry and interconnections thus creating transmission and processing bottlenecks in the networks or with computers, workstations, and telecom central offices. The prime facilitator or enabler has been the development of optical comm. This demands both the technological capability and a manufacturing infrastructure for producing optical interconnect components and circuits in high volume which are deployable at economically acceptable costs with environmentally robust packaging, and with acceptable performance. Because of the urgency to mass deploy optical interconnects there are indications² of a willingness to compromise some aspects of performance for lower costs and higher volume in order to drive the growth of the required manufacturing infrastructure.

These optical interconnection needs are increasingly thought resolvable through the use of optical polymeric planar waveguide systems. Polymers for optical interconnects have long been thought to have promise due to their inherent process, property and applications versatility combined with potential for high volume, low cost production. Substantial developmental activity has been underway world wide in an attempt to exploit the potential of polymers for creating waveguide circuitry for telecom and datacom applications.³ Polymer waveguide systems have been shown to be able to employ either single or multimode waveguides and can encompass passive point-to-point or functional interconnections, such as splitters, couplers, and taps; wavelength selective multiplexing or WDM's; and active slow millisecond routing switches or fast non linear polymeric GHz modulators / switches. They can take the form of rigid circuit board based or flexible circuitry, or stand alone fiber coupled components. Demonstrated performance and application capability for some polymeric integrated optical components and circuits suggests that the long anticipated promise for optical polymers is coming to pass as a key realization for the age of photonics.

The critical technical issues for successful polymeric waveguide systems consist of waveguide formation, which involves both polymer materials and processes, and connectorization and packaging that provide a system that meets acceptable operational, processing, environmental, and lifetime performance. However, of increasing importance due to obvious market urgency is the over-riding issue, assuming acceptable performance, of system manufacturability with reasonable volume and economical cost effective implementation. In short, you can have the best low loss waveguide circuit / component in the world, but if it is not stably connectorized and packaged for practical low loss interfaces, it is not useful. Likewise if it is not amenable to reasonable low cost high volume manufacture and not easily implemented or installed in optoelectronic systems, it is not a practical solution. DuPont's Polyguide(tm) system, even though it is still being continuously enhanced, currently has superior demonstrated relevant attributes which should enable it to meet nearly all important system needs as will be described in the remainder of this paper. Because DuPont is committed to bringing their photopolymers to the optical interconnect market the Polyguide(tm) program has been transferred from the Central Research Department to a new business unit, Photopolymers and Electronic Materials to actively develop the Polyguide(tm) business based on polymeric material supply to photonic system manufacturers.

POLYGUIDE(tm) OVERVIEW

Polyguide(tm) technology produces single and /or multimode waveguides in film sheets that are buried through lamination of multiple surrounding polymer film layers. Lamination to or between other high Tg layers or substrates provides for stable packaging and low loss interfacing to optoelectronic systems such as diode lasers, detectors, waveguide devices, or optical fibers. These layers dominate the thermal mechanical properties of the guide structures. Recent advances have pertained to the use of high Tg Kapton® polyimide packaging combined with moisture protection layers for 85°C and 85%RH conditions. Stability during thermal spiking solder processes to assure that Polyguide(tm) photonic systems can be incorporated onto electronic circuit boards was demonstrated. Important developments reported as examples include DARPA funded POLO program data link waveguide structures and POINT program optical backplane daughter board super dense connectorization demonstrations. Also described are results on single mode connectorization and associated waveguide stability performance from packaging developments. Broad optical functionality has been confirmed for Polyguide(tm) single and multimode systems in laboratories in the United States, Europe and Japan. Although not reported here, the University of Gent in Belgium (as part of a thesis program) using Polyguide(tm) multimode waveguides has recently published results of an extensive experimental and theoretical study of numerous high performance optical function designs including bends, splitters, star couplers, crossovers, taps, and mode scramblers.4-6

UNIQUE ATTRIBUTES OF THE POLYGUIDE(tm) SYSTEM

Ultimate system performance and manufacturability is determined and constrained for any polymer waveguide system by the selection of polymer materials, waveguide and structure formation processes, connectorization and packaging options. Fortunately Polyguide(tm) depends on a synergistic combination of unique attributes for these options which are highlighted below.7-15

Precoated polymer materials - Waveguide forming films with acrylate and methacrylate monomers and polymer binders along with initiators and other constituents are mixed, filtered at the tenth micron level, and precoated on a temporary Mylar® substrate carrier with a Mylar(tm) protective cover sheet and rolled in several hundred foot lengths for storage. Coating thickness accuracy and in-run precision routinely provides reproducible homogeneous waveguide forming properties. Adhesion layers and precoated Kapton® or other packaging layers are similarly prepared. Numerous photopolymerizable liquid formulations are used for bonding, planarizing, protecting or molding.

Capitalizing on precoated solvent free polymer materials enables Polyguide(tm) to provide a reliable and reproducible semi-automated waveguide structure assembly process. Large waveguide film structures limited only by the size of a single photolithographic mask exposure can provide either circuit board size circuitry or multiply imaged components for reduced unit cost group machining, packaging or other processing steps.

Waveguide formation process - Waveguides are formed with proprietary techniques based on internal diffusion of monomers to create optical waveguides. The processes exploit the polymeric property that high mobility low molecular weight monomers can rapidly diffuse within a polymeric binder matrix. The process is dry, with no etching or molding. Guide formation is completely light induced at low 15 to 45°C temperatures followed by photo and thermal fixing. Smooth, low scatter waveguide side walls are produced resulting in optical losses inherently identical to the bulk materials. This results from having waveguide edges within the guide layer defined by monomer diffusion, induced by photolithographic and photopolymerization processes, and from having the waveguide top and bottom defined by the coated film surfaces that are flat to tens of nanometers. Current waveguided optical losses are summarized in the table in Figure 3 along with other important characteristics. Different formulations are used for single and multimode guides. Single mode materials are being reformulated to achieve even lower losses at long wavelengths. Polyguide(tm) waveguide formation is a straight forward process with minimal equipment and steps, uses dry, precoated and pre-quality controlled materials, and is amenable to large area exposures, as opposed to etching, molding, or embossing procedures.

Single Mode Process - To create single mode guides we utilize diffusion into the exposed guide region followed by buffer / clad layer diffusion between all layers as depicted in Figure 1. As usual an entire large area photoexposure locks up remaining monomer after diffusion has occurred, thus fixing the system. Bake / curing steps further stabilize the structures. This enables formation of single mode channel guides ranging from several microns to 12 microns depending on guide design and index. Typically dimensions are designed around 6 μm to match telecom fiber 9 μm mode fields. A variety of shapes and sizes are possible. For example, in-plane free divergence guides where light is unbounded or unconfined horizontally for several hundred microns have no mode structure and a gaussian divergence profile which facilitates novel splitter designs and wavelength selective devices. Vertically they operate single mode with around 6 μm confinement. Waveguide indices relative to the uniform lower index surrounding clad region can be controllably reproduced and are extremely uniform across and along the guide. For single mode propagation, the guide index can range from 0.003 to 0.01 by adjusting the exposure parameters of power, energy, and temperature for a given formulation. However, typically it is adjusted to be near 0.0055 to match the NA of telecom single mode fibers.

Multi-mode Process - To create multimode guides the initial guide forming exposure locks up or polymerizes the large multimode region's monomers, minimizing, through control of exposure conditions, any primary diffusion into the guide edges to assure a uniform guide profile. Buffer / clad layers are laminated to both sides of the guide layer. For multimode guides these layers are a different formulation with reduced diffusible monomer content that produces a lower fundamental bulk index. The unexposed monomer in the guide layers outdiffuses into the surrounding buffer layers reducing the index relative to the exposed guide region and equalizing the index of all except the guides. This secondary diffusion reaction is schematically shown in Figure 2. Guides of any size can be reproducibly formed with relative guide indices as high as 0.05 by adjusting exposure parameters or altering formulations. Exposure parameter variations have enabled index profiling at the guide edge for enhanced coupling to graded index fibers. As usual final light fixing and baking create a stable structure.

Lamination Process - The ability to progressively laminate and bond successive layers to build up Polyguide(tm) structures provides a significant and essential attribute for performance, applicability and manufacturability. Using pressure and temperature controlled laminators with precoated materials adjusted for adhesion properties bubble free high quality multilayered bonded structures are created. Polyguide(tm) waveguide, buffer / cladding, and adhesion layers are precoated on exceedingly smooth Mylar® as a temporary carrier. After lamination and photopolymerization the Mylar® is peeled off and discarded. Some key benefits of the lamination attribute include:

- Symmetric structures of nearly any desired thickness are routinely made that have submicron centering precision for buried waveguides. This is particularly important for aligning optical fibers for coupling to single mode waveguides.
- Controlled interdiffusion between initially unpolymerized layers obliterates any boundary and enhances bonding.

- Bonding of package layers noted below through lamination using adhesion layers is critical to meet performance specifications.
- Large film structures can be easily processed producing large numbers of components or larger circuits.
- The entire packaged structure assembly is amenable to automated and high volume processing for low cost manufacture.

Machining Processes - Polyguide(tm) is amenable to accurate computer controlled automated cutting essential for low optical coupling losses and economical manufacturing. Key attributes are:

- Precision micromachined structures for alignment to fibers, guides, EO circuits or components are cut or ablated using focused laser radiation such as from excimer lasers.
- Computer controlled translation stages permit automated cutting with micron precision of an entire exposed Polyguide(tm) wafer with potentially hundreds of components. Submicron precision has been achieved for fiber or EO device alignment slots. Rapid singulation has also been achieved under automated computer control. Microtome based cutting is employed to make long mirror cuts where angularly oriented smooth surfaces are needed or for optical input edges during guide evaluation.
- Planarizing with photopolymerizable Polyguide(tm) liquid formulations with matched indices and designed bonding properties facilitates interfacing and improved mirror construction.

Packaging - Polyguide(tm) system performance stability under all operational and storage conditions is achieved through lamination and bonding of packaging layers with desired properties. High Tg and low CTE polymers provide thermal-mechanical and environmental robustness and performance stability through their complete domination of the Polyguide(tm) packaged structure properties. Packaging materials have included DuPont's polyimide Kapton®, polycarbonate, and various inorganic and metallic layers or coatings. Some resulting attributes are:

- Kapton® inherently has a CTE of around 20 ppm and a Tg near 350°C. Packaging with Kapton® produces effective Polyguide(tm) waveguide CTE's between 25 to 35 ppm for multimode and single mode structures respectively. Kapton(tm) packaging enables process stability under standard 230°C thermal spike soldering processes for guide pitch and cantilevered structures; for example, unsupported guides overhanging VCSEL's. Excellent CTE match is achieved for fiber array holder spacing for fiber coupled components and for EO components located on silicon or ceramic, all important for stable optical interfaces over typical operating temperature ranges. The CTE is well matched to standard circuit boards for hybrid OPWB circuits.
- Polycarbonate inherently has a CTE around 70 ppm and a Tg near 150°C. Packaging with polycarbonate produces effective Polyguide(tm) CTE essentially identical to these values. In addition, allowing the packaged structure to reach around 155°C it will easily conform to desired bends or configurations. Upon cooling below the Tg the shape is permanent and optical losses are not impacted down to 4mm ROC with 180° hair pin bends for current multimode guides.
- Inorganic and metallic coatings and layers placed over and/or encapsulating Kapton® packaged Polyguide(tm) guides have demonstrated excellent moisture protection with no moisture induced optical losses for greater than 1000 hours at 85°C and 85%RH. Metallic electronic runs have been directly soldered and evaporated onto Polyguide(tm) layers with similar electronic properties as Kapton® that is used commercially for flex circuits or on board substrates.

Connectorization - Connectorization techniques rely on computer controlled precise laser micromachining of large multi-component wafer exposures as the principle means to achieve the required precision for either single or multi mode optical fiber array coupling. For single mode accurate positioning is achieved in two stages. First level precision to nearly one to two microns is with CTE matched fiber array holders. The second level of precision to submicron levels is achieved upon fiber insertion into slots micromachined into the guide structure before packaging with high Tg polymer. Similar micromachining tools are used for less demanding multimode MT connectorized Polyguide(tm) waveguides for arrays or board level coupling as noted under the POLO and POINT program results below. The entire symmetric laminated structure and high Tg packaging facilitates the connectorization process producing low loss coupling. Mirrors and other slot to slot coupling approaches have been described elsewhere.

System Design Versatility / Customizability - Some other unique Polyguide(tm) capabilities and system properties not noted above but which offer considerable latitude for design and implementation of optical interconnect circuitry are summarized below:

- Waveguide and bulk index properties are extremely stable over desired wavelengths and temperatures. The bulk index remains constant over the 600nm to 2000nm range as measured using comb spectra. Bulk index as a function of temperature measured using an Abbe refractometer over 0°C to 60°C (measured range) changed linearly by 2.9×10^{-4} , typical of most polymers. The guide index as a function of temperature and wavelength was monitored using far field divergence angles and is stable over the standard operating range up to 85°C. Degradation due to high optical power has not been observed as is summarized in the table.
- No polarization effects induced by molecular orientation in the guides have been observed as the polarization of input light seems to be maintained within the sensitivity of the measurements. The polymers, as coated from a solvent, are homogeneous and polymerize with no preferred orientation axis. Furthermore, lamination and bonding processes do not introduce any stress induced molecular orientation.
- Waveguide spacing for multimode guides has been demonstrated down to 10 μm for 10 cm long guides with crosstalk down by at least a factor of - 30dB. This permits high density guide circuits and connectorization schemes. Single mode guides have been shown to evanescently couple up to around 20 μm spacing and thus must be separated further to insure no crosstalk for guides with matched propagation coefficients. Highly efficient evanescent couplers have been constructed with spacing down to 2 microns.
- Fundamental polymer resolution is extremely high such that structures with sub micron sizes are easily imaged. Gratings with at least 5000 l/mm have been constructed. Thus mask designs must have steps from e-beam writing that are 0.1 μm or less to prevent undesirable optical losses on curves.
- Diffraction gratings can be created which are either in or around waveguides for WDM devices. The diffusion process that creates the guides also constructs Bragg gratings using holographic techniques. 14
- Multimode guide index profiles resulting from alternate exposure conditions enable a reduced guide index near the guide edges in a graded index profile to concentrate light in the guide center for better coupling to graded index optical fibers.
- Preliminary results indicate thermal degradation due to continuous exposure to elevated temperature increases optical loss by $10 \exp^{-6}$ dB/cm/h with current single mode formulations extrapolated for operation at 85°C and monitored at 1300nm. This level would increase losses around 0.01 dB/cm per year. Multimode formulations are even more stable. Testing continues.

Facilities - Required capital investment to manufacture Polyguide(tm) components and circuits is fundamentally low.. Specifically the equipment and apparatus required for creating and assembling guide structures is a standard exposure box and laminator for assembling and packaging. This requires an investment less than \$50K assuming that a clean room or tent is available. The extent of automation and throughput will dictate the total cost The major investment is the laser micromachining system which can run up to \$200K or more depending on size, controls, and throughput. Obviously measurement systems, control hardware, testing apparatus, microtome, microscopes, etc., will add additional but modest costs typical for other programs.

Application Options - System versatility, overall performance and configurability are key attributes for the applications denoted below as examples which during the presentation will be the focus of the discussion.

POLYGUIDE(tm) APPLICATION EXAMPLES

Optical interconnect applications being investigated or developed by our licensees, AMP and Hewlett-Packard, demonstrated by DuPont, or developed under DARPA POLO and POINT consortium funding include various forms of connectorized point-to-point data links, optical circuit board technology with multi array connectors, and fiber coupled splitters as key generic examples indicative of the scope of Polyguide(tm) system technology. The presentation will include photos, schematics, and data for these applications relating to the important attributes reviewed above.

Telecom / Single Mode Components

Single mode components are typically fiber coupled due to the permanency of telecom installations. After Polyguide(tm) waveguides are exposed and symmetrically laminated to a thickness nominally around $122 \pm 2 \mu\text{m}$, laser micromachined slots with similar widths and typical $1000 \mu\text{m}$ lengths are precisely centered at the ends of the waveguides. Package layers which are either Kapton® or polycarbonate are then laminated top and bottom leaving slots with square cross sections. The components are singulated from the large area exposed wafer such that the end of the square slots are accessible. This is depicted in Figure 4. A fiber array is constructed using precise templates and/or molds to create grooves on Kapton® or polycarbonate, or alternatively soldered using metalized fibers to create hermetic seals based on standard commercial processes. The fiber array spacing is identical and CTE matched to the waveguide. The fibers protrude from the fiber array holder typically 3mm to allow sufficient fiber flexure for the second level of alignment precision as they are pushed into the square slots centered on the waveguides. Photopolymerizable liquid Polyguide(tm) enters through an ablated trench or manifold entering the slot at the fiber to waveguide junction. Any air pockets are thus removed for optimum coupling. It is then polymerized and by formulation design bonds to the glass fiber and to Polyguide(tm). Hermetic package sealing is achieved by encapsulating the fiber coupled component as depicted in the figure.

Some results for single mode fiber coupled systems:

- As an example a recent Polyguide(tm) single mode polycarbonate packaged 1x8 splitter produced 2.2 dB excess loss at 1300nm with a ± 0.35 balance. Waveguide loss was about 1 dB and the three Y junction splitter losses usually total around 0.4 dB. Fiber to waveguide distance axially was inadvertently left about 15 to 20 μm producing at least 0.5 dB. Thus misalignment losses were less than 0.2 dB per couple.
- Investigation of hermetic sealing for a sealed Polyguide(tm) fiber coupled waveguide has thus far resulted in no moisture induced optical losses when at 85°C and 85% RH for 2000 hours. Moisture penetration into an unprotected guide can rapidly increase optical loss by nearly 1 dB/cm at 1550 nm within 20 minutes under these extreme conditions. Thus the hermetic sealing achieved in our process is extremely effective and expected to meet Bellcore specs.
- A single mode fiber coupled guide made using our evolving modified acrylate formulations and packaged with Kapton® for the first time was thermally cycled from around - 55°C to 85°C with reproducible performance and minimal ± 0.2 dB throughput

deviation between temperature extremes. Kapton® packaging provides increased stability, robustness at high temperatures, and imposes a matching CTE between waveguides and solid state components or circuit boards. In addition, it also reduces thermal stress during temperature cycling and thus suppresses repeatable optical thruput variations with temperature that seem to be inherent in many polymer waveguide systems. Thermally induced stresses apparently induce polymer molecular level configuration changes that impact guide propagation.

Datacom / Multimode systems DARPA funded optical interconnect programs

Two current DARPA funded programs, POLO (Parallel Optical Link Organization) and POINT (Polymer Optical Interconnect Technology), utilize polymeric optical interconnect technology and are aimed at application demonstrations that can lead to low cost manufacture for circuit board optical interconnects and data links. Both utilize DuPont's Polyguide(tm) technology.

- The POLO program involves Hewlett-Packard, AMP, University of Southern California (USC), DuPont, and SDL as consortium members and is aimed at developing the technology for a high performance low cost manufacturable optical data link system. 16-20 The data link module employs a flexible Polyguide(tm) waveguide interconnect between fiber arrays (AMP/DuPont) and the VCSEL's (HP), plus advanced connector designs (AMP), and drive electronics (USC). Using Kapton® packaged POLO guides, dimensional, mechanical, and optical stability during and after standard 230°C solder process temperature spikes was demonstrated. Encapsulation with SiOx layers has shown promising moisture protection for transparent optical interfaces with work in progress to meet long term exposure requirements. Balanced low loss MT style array guide to fiber connection coupling is thermally stable over the entire operating range for a complete POLO Tx and Rx data link meeting all loss budget goals. Details of the POLO module data link performance have been reported elsewhere.

An alternative POLO option aimed at aerospace applications is being developed by SDL. Edge emitting lasers are interfaced to a fiber array with rigid packaged Polyguide(tm) waveguides encapsulated between two sets of MT connector style pins. The double pin set MT connector approach is shown in Figure 5. The wide 9.2 mm pin set interfaces directly to etched grooves in silicon for precision alignment of the encapsulated waveguides to an array of edge emitting diode lasers. Interconnection to a commercial MT fiber array uses the standard narrow set of pins. The Polyguide(tm) optical bridge, which is mounted in the wall of SDL's transmitter package, provides for mechanical stress decoupling between diodes and fiber connector with optical coupling enhancement from tapered high NA guides. Balanced operation for the entire link system within ± 0.5 dB has been demonstrated thus far up to 622 Mb/s with a good open eye pattern as reported by SDL.

- The POINT program is focused on board and backplane technology. 22-27 Consortium participants are General Electric, Honeywell, AMP, Allied Signal, Columbia University and USC. Results have been extensively reported elsewhere. Recently AMP has reported a "super MT" high density connector system using Polyguide(tm) with multiple MT connectors on a backplane. As an example, a daughter / backplane interface was reported with 144 Polyguide(tm) waveguide channels, 50 μ m core guides spaced 100 μ m apart. The link included two 45° mirrors, four connectable interfaces, 27.8 cm of waveguide producing and excess loss of 10.5 dB, well below the loss budget limit. Other "super MT" connectors provided 250 signals per board edge inch. Overall optical waveguides produced a 5 to 1 signal density advantage over electronics.

Successful application of Polyguide(tm) waveguides and interconnections on optical-electronic hybrid circuit boards as demonstrated by the POINT program and in previously reported work suggests that "the real technology leap is coming with optical and electronic elements combined on large-scale integrated circuits (ICs)". 2

Other programs

Both AMP and Hewlett-Packard have licensed Polyguide(tm) technology and are exploring numerous other single and multi-mode product development applications. In particular, HP is developing a LAN WDM multimode system using Polyguide(tm) aimed at combining / separating a number of wavelengths to maximize data transmission rates in single fiber systems. 28

SUMMARY

The information revolution is gathering momentum and must soon begin mass deployment of optical interconnections to enable optical fiber based networks to be effectively interconnected to the end users, networks, and computer systems. Technology and manufacturing infrastructure are required that meet these needs. Polymeric photonic interconnection systems offer great potential to achieve both requirements. Polyguide(tm) technology is believed by many to have the breadth and potential for both single and multimode applications to meet optical and system performance, operational and environmental robustness, and economical manufacturing assembly processes that meet marketplace needs.

PATH FORWARD

To meet the long term challenge and satisfy the needs of the information age through photonics the Polyguide(tm) system technology is being continuously improved. This includes optimization of processes, materials, packaging and connectorization with a particular emphasis on economical high volume optical interconnect component and circuit manufacturing assembly process as the key for marketplace success. DuPont is bringing to bear its photopolymer expertise and state of the art polymer film coating facilities as part of the essential manufacturing infrastructure, which can provide substantial quantities of high quality optical polymer materials to meet industry demands for some time to come. With the shift to a business focus within DuPont we are optimistic that we can meet these goals working with our customers to commercialize their optical interconnection circuitry products.

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27. Y.S. Liu, W.B.Hennesy, R. Wojnarowski, J.P. Bristow, Yue Liu, J. Rowlette, J. Stack, M. Kadar-Kallen, J. Yardley, L. Eldada, R.M. Osgood, R. Scarmozzino, S.H. Lee, S. Patra, "Optoelectronic Backplane Interconnect Technology Development - POINT", Invited Paper "Optoelectronic Interconnect and Packaging IV", Photonics West '97, Feb 12, 1997.
28. B. Lemoff, Hewlett-Packard, paper submitted to OFC97' postdeadline session

POLYGUIDE(tm) SINGLEMODE WAVEGUIDE EXPOSURE PROCESS

1. Exposure

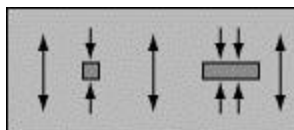


2. Primary Diffusion

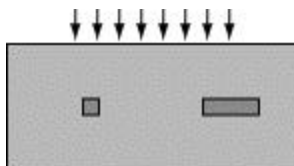


3. Lamination

4. Secondary Diffusion



5. Photo Expose Flood



6. Cure / Crosslink



Figure 1. Polyguide(tm) single mode exposure process steps. Both primary and secondary diffusion are important for creating a robust film structure and uniform guides of different widths. Waveguide and buffer / clad layers are identical. Typically, exposure power is 14mW/cmsq. and energy is 100mJ/cmsq. Standard light box mercury arcs are used. Baking is usually at 135°C for 2 hours. Exposure temperatures are varied to produce different guide indices.

POLYGUIDE(tm) MULTIMODE WAVEGUIDE EXPOSURE PROCESS

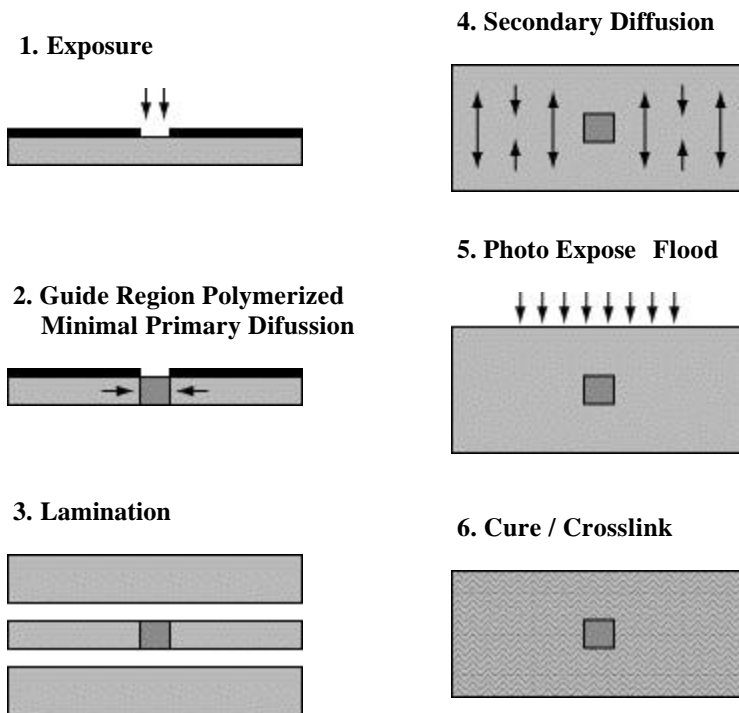


Figure 2. Polyguide(tm) multimode exposure process steps. Secondary diffusion is the dominate mechanism for forming large uniform waveguides. The waveguide and buffer / clad layers are distinctly different formulations to create desired guide indices. Typically, power is around 5 mW/cmsq. and the energy is 30 mJ/cmsq. using standard light box mercury arc. Baking is usually at 135°C for 2 hours. Exposure temperature is around 40°C.

POLYGUIDE(tm) CHARACTERISTICS

Operating Properties:	Acrylate Based (multimode or single mode)	Modified Acrylate (single mode)
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Optical Losses

@ 800 nm	0.08 dB/cm	0.12 dB/cm
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@ 1300 nm	0.35 dB/cm	0.20 dB/cm
@ 1550 nm	1.6 dB/cm	0.60 dB/cm
Relative Guide Index	0.002 - 0.05+ SM to MM	0.004 - 0.015+ SM
Bulk Index	1.485 - 1.51	1.46 ±0.02
Optical Power	Sustained SM at 1300nm for 276h+ at 20mW thrupt (55kW/cm ²) and > 150 kW/cm ² for 10 hr.+	
Processing T	<ul style="list-style-type: none"> • Guide construction curing 2 to10 hours 135°C • Waveguides sustained 200°C for 10 min with no change; • Kapton® Packaged --withstands 260°C solder spike T profile 	
Operational T Range	<ul style="list-style-type: none"> • Multicycled -55°C to 150°C+ • Sustained 2+ weeks 125°C; 6+ weeks 85°C 	
Moisture/Unpackaged	High RH / moisture induced losses eliminated upon baking	
Effective CTE	<ul style="list-style-type: none"> • PC pkg. 55 to 90 ppm • Kapton® pkg. 26 ppm 	
Effective Tg	<ul style="list-style-type: none"> • PC pkg. 145°C • Kapton® pkg. 240°C+ 	
Guide Size Range	4 μm to 200+ μm (height and/or width)	
Dielectric Const	3.2 @ 10 GHz	
Breakdown Volts	100 v/μm	
Photopolymer Liquid Viscosities	20 to 150 centipoise	

Figure 3. Polyguide(tm) characteristics including optical, mechanical, thermal, and environmental properties

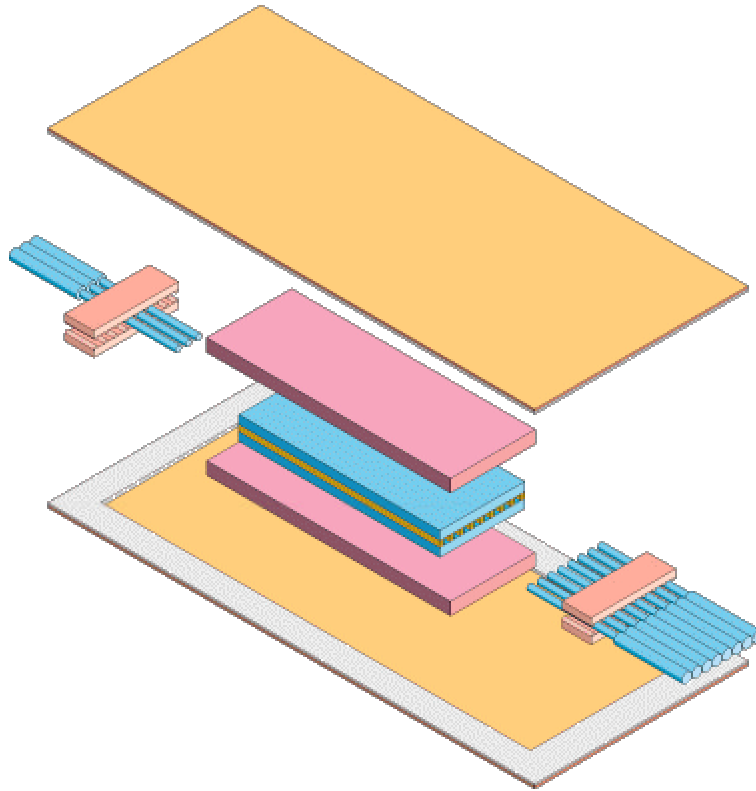
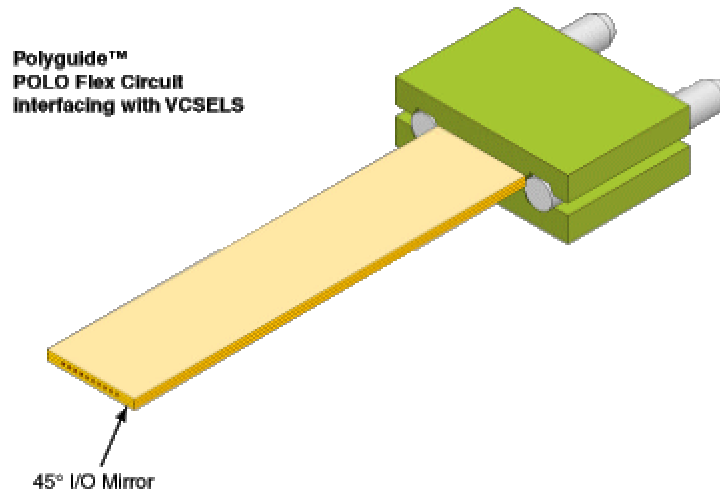


Figure 4. Single mode fiber coupled Polyguide(tm) waveguide structure and packaging configuration. Excimer laser micromachined slots orient the inserted fibers in a precise alignment procedure. Fiber arrays are precisely positioned with molded grooves or equivalent to provide initial alignment . External high Tg polymer layers provide for a robust rigid structure. Additional layers are used to provide hermetic packaging capable of surviving 85°C and 85% RH.



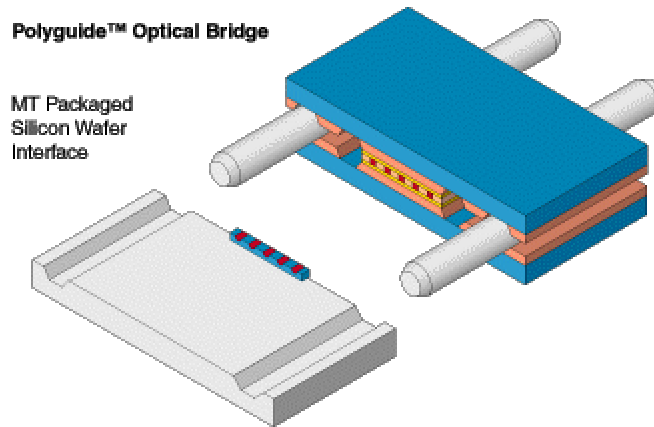


Figure 5. (top) POLO (Parallel Optical Link Organization) developments for Tx and Rx modules for interconnecting computer workstations, include a flexible waveguide link between the VCSEL's and fiber array MT style connector. They are designed to be capable of withstanding thermal spikes to 230°C during electronic soldering processes. This form of MT connectorization is also useful for optical circuit interconnections between fiber arrays and daughter and backplane boards.

(bottom) POLO link design being developed by SDL for aerospace applications using edge emitters mounted on a silicon wafer. Alignment to a Polyguide(tm) MT style connector interfacing to silicon grooves is shown. The MT connector is mounted on the face of the metal can protecting the electronics and optical interface. Direct interface to silicon provides an optical bridge for thermal and mechanical stability, alignment precision and assembly, as well as mechanical decoupling and optical functionality for enhanced coupling efficiency.