OPTICAL iNTERLINKS

Comparison Review Highlights Between OIL's Diffusion Based GuideLink™ Technology and Conventional Guide Forming techniques---------

as of November 2015

Current practical polymer waveguide formation technologies

use either one of two generic processes *.

Waveguide formation is achieved by:

1) ***Optical InterLinks Proprietary GuideLink™ Technology*:** **Monomer in-diffusion into light imaged polymerizing waveguide to create higher polymer density / refractive index guide channel.** Subsequent total polymerization of surround leaves residual higher index waveguide. Added clad layers using nearly identical diffusable formulation creates buried waveguide in uniform surround.

2) ***Conventional Technology used by All Others:*** **Etching, molding, or embossing to create ridge/rib (or trench) waveguide channel**. Subsequent different index polymers used with backfill steps and/or clad lamination to form buried waveguide.

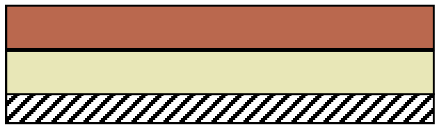
*Conclusion from 2005 iNEMI consortium project on optical backplane/daughter board interconnections. Results report in 2006 APEX meeting.

Generic Etching, Molding, Embossing Waveguide Creation Processes-

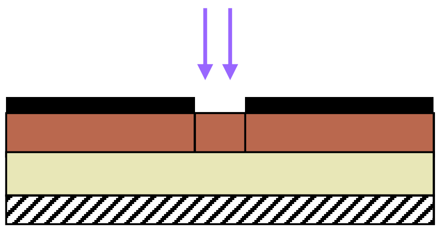
Ridge Formation

1. Deposit clad layer polymer on Substrate

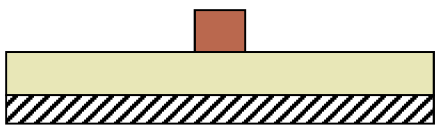
2. Deposit WG layer on clad layer



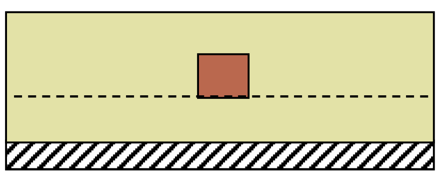
3. Photo image WG region to enable etching removal of WG layer polymer outside of WG



4. Etch remove WG layer polymer outside WG

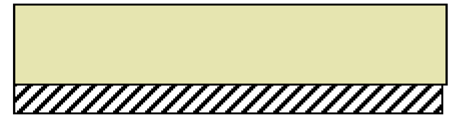


5. Backfill with clad layer polymer---Substrate remains

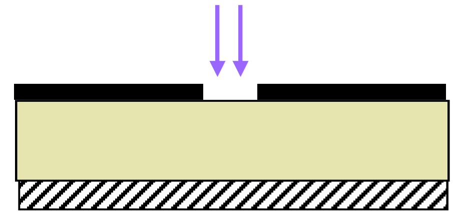


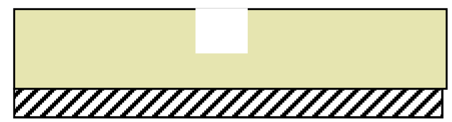
Trench Formation

1. Deposit clad layer polymer on Substrate

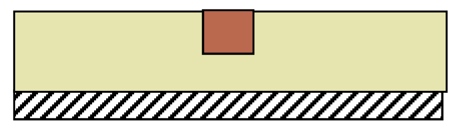


2. 3. Photo image WG region to enable etching removal ---alternative routes use mold or embossing tool--- to create a trench-

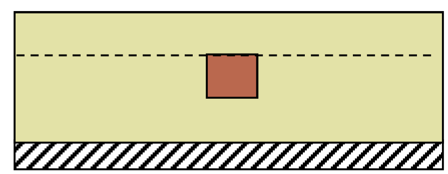




4. Backfill WG polymer into trench



5. Backfill over coat clad polymer---Substrate remains



From OIL's perspective: major issues with etching, molding, embossing waveguide creation techniques are;

- **Waveguide side walls are often not smooth (have > 0.1 micro roughness) due to etching process or contact with mechanical tools and thus scatter light, adversely impacting waveguide loss and in-plane curvature radius loss threshold.**

- **Backfill for final cladding layers can trap bubbles that scatter light.**

- **Due to the necessity for polymer removal by etching, or use a micro tool for molding/embossing, the pitch or minimum waveguide spacing is limited and waveguide junctions are blunt or not sharp so they scatter light making lossy splitters, combiners etc.**

- **Others—specifically different polymers required for guide and cladding to balance guide index; etching requires use of disposable solvent in liquid form for in-situ processing/coatings, -----**

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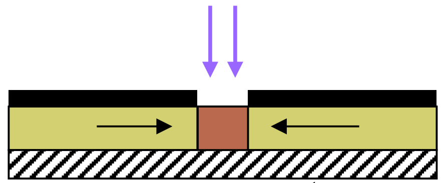
GuideLink™ Waveguide Process --- all layers are

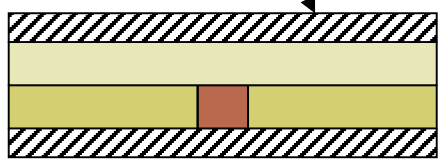
Monomer + Polymer Formulations pre-coated on Mylar

1. Photo expose – WG layer Diffusion



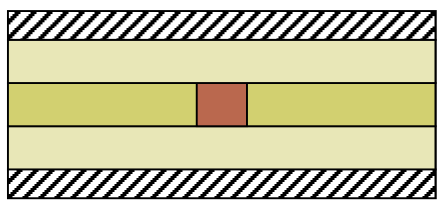
Mylar –temporary substrate

2. Add Clad layer #1

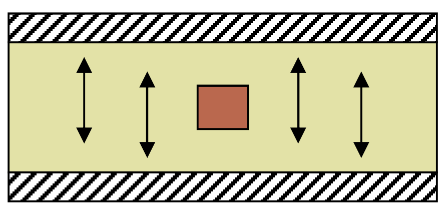


3. Remove WG layer Mylar add

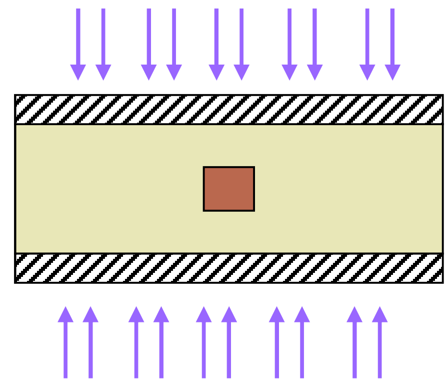
Clad layer #2



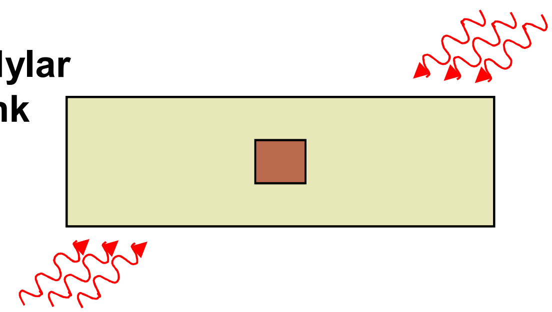
4. Interdiffusion of monomer in all film layers



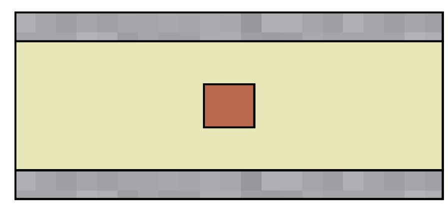
5. Total photo polymerization– to all polymer



6. Remove Mylar Bake crosslink



7. Add Robust polymer layers: High Tg Low CTE



OIL's Waveguide formation process provides unique capabilites

1. Very smooth side walls for low loss minimal ROC

2. High density close spaced waveguides

3. Very sharply defined functional features with high resolution are formed ---
   - sharply defined split junctions between two waveguides (polymer does not have to be removed and backfilled with a lower index polymer),
   - low index imaged regions inside waveguides can deflect or scramble modes, and create barriers to reduce crossing guide loss and for sensors/WDMs

4. Monomer formulations are re-configurable for continuous range of guide properties yet preserving the unique diffusion based process

5. Graded index polymer waveguide profiles can be created with proper exposure

6. Extremely versatile configurability for diverse applications, operationally and environmentally stable

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OIL's GuideLink ™ attributes:

- Self developing monomer diffusion process requires no etching, embossing, molding or any contact or removal to create waveguides
- Monomer diffusion created waveguides provide extremely smooth side walls (< 0.1 µm) enabling high guide density, small ROC, sharply defined split/guide junctions, mode scrambling, ~low loss crossovers etc.
- Pre-coated on a temporary Mylar substrate in strips or on rolls up to hundreds of feet long that are later removed during processing/lamination of dry layers
- Film coatings have uniform properties w shelf life in years
- Waveguides, and waveguide and clad layer polymers are nearly identical monomers with diffusion providing the higher index waveguide so that
- Waveguide and clad refractive index difference is thermally independent for stable determines guide properties ---most important for single mode
- Multiple monomer formulations are re-configurable without radical change of constituents or process permitting a continuous range of NA (0.15 to 0.3) as well as other property modifications being investigated
- Rugged packaging layers on each side of WG for effective low CTE, high Tg, mechanical & environmental robustness, self supporting or substrate bonded circuits
- Process is most amenable to high volume processing using pre-coated material on rolls
- Waveguides are configurable, stackable, flexible, easily laser or mechanically machinable for a broad range of products

GuideLink™ Specs--optical & waveguide (WG) properties

● **Optical loss:** 850 nm ~0.1dB/cm; 980nm 0.25dB/cm;1300nm 0.35dB/cm, 1550nm 1.25dB/cm --identical to fundamental loss and independent of guide size –due to smooth < 0.1 µm micro roughness

● **Waveguide refractive index / (Index contrast Δn)** from 0.003 to 0.04 higher than surround bulk index of 1.505: typical MM guide Δn for coupling to OF with 62.5 µm GI core ~0.033 and for OF with 50 µm GI core ~ 0.018 over surround aimed to match NA; and Δn temperature & wavelength independent over operating range

● **Coupling loss:** WG to WG < 0.2 dB NA and size matched; WG to GI OF ~0.7dB assuming optimized guide size to couple to high index center w Tx WG < 2/3 OF core; and Rx WG ≥ OF core; I/O mirrors <0.4dB low and high mode fill; for high mode fill need metalized mirror

● **System loss dominated for < 30 cm guide lengths** by OF coupling to/from OF and solid state components; involving NA mismatch and size issues, I/O mirrors, I/O surfaces, alignment offsets; OIL can tune for NA, has smooth walls, excellent I/O surfaces, in-plane and out-of-plane bends have equal loss to small ROC,

● **MM WG dimensions** 10 to more than 100 µm rectangular or square, hero to 300 micron size; and MM guide to guide **spacing** 4 µm and up permits high density

● **ROC min identical for in-or out-of-plane---**scales with width in bend plane: 50 micron guide ~5mm; 35 micron ~3mm; 15 micron ~1mm

● **Stable substrate bond** to glass, ceramic, FR4, semiconductors

GuideLink™ Specs--optical & waveguide (WG) properties

● **Operation T** **–55 ºC to 125 ºC**; waveguide formation includes bake / cure 3 hrs at ~130 ºC

● **Arrhenius plot data** **---Long term 850nm at 85°C for 5 years results in 0.1dB/cm loss increase**; at 1300nm 0.01dB/cm

● **Monomer/polymer solvent mix stabilty** **-- months to years** before coating;

● **IR solder reflow** **waveguides and mirrors survive 230 ºC spikes for ~30 sec** for flip chip bonding of electronic components over or near waveguides

● **Coated but unexposed monomer / polymer film stability--** **many months to year** (hero 5years)

● **Environmental moisture**: **OIL packaged waveguides are stable in the range equal or lower to ~ 40C at 85%RH, the anticipated maximum extreme temperature and humidity occurring naturally in the world.** For every 10C increase RH decreases 2x and vice versa (see Wikipedia), so real world conditions will always have lower humidity at higher temperatures. Elevated conditions beyond this are due to accelerated aging testing which may not be relevant for the need and could activate failures not seen operationally.

● **Environmental testing comment :**
Testing under 85C/85%RH for extended periods **is aimed at uncovering /activating potential dormant failure modes** to provide insight into accelerated aging situations**-- but not to introduce failure modes that would never occur in normal operation.**

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GuideLink™ Specs -- optical & waveguide (WG) properties

● **Bend cycles** greater than 4000 demonstrated so far with 2mm ROC and 180° bend with no apparent performance loss optically or mechanically

● **Dielectric constant**: 3.2 at 10MHz; breakdown voltage > 100 V/µm

● **Film / optical I/O edge cleaning** with petroleum ether (PET); alcohols / other solvents create light scatter damage; protection achieved with epoxies

● **Polarization independent** **--** homogeneous

● **Open eye diagram** high frequency propagation at 10GHz, 13 cm

● **Radiation dose** no impact to date; 100kRad for γ; 6 Mega Rad 37 Mev protons

● **Out-gassing Study by NuSil -** collected volatile solids 0.09% spec <0.1%

● **Optical power** no impact: 150kW/cm2 ; 100mW guided all wavelengths to date

● **Packaging/jacketing layers dominate** CTE at 60ppm, effective Tg at ~200 ºC; with nominal Young's modulus at 2.9GPa; tensile strength 100MPa

Bio related:

● **Simulated in vivo environment successful ---** waveguides with metalized I/O mirrors survived 40°C for ~ 4 days in water / 3% saline solution

● **Enzyme exposure ---** repeated use of a bio enzyme had no impact on guiding or optical capillary wall properties;

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Presentation summary :

OIL's Polymer Waveguides as Building Blocks for optical interconnectivity

Configurations

- Flexible film sheets / strips, precision interconnections created with micromachining or die cutting, substrate attached if needed and
- Polymer guides coupling to/from optical fibers for hybrid systems – *capitalizing on the strengths of polymer waveguides and fibers*

NA and guide dimensions

- Matched for Tx and Rx for PWG (step or GI) to/from GI OF ("sweet spot"); formulation modifications permit versatile coupling control. *By varying multiple monomer ratios OIL is able to tune the waveguide NA to meet different OF requirements*.

Connectivity

- MT or microMT style array connections – board edge/film edge
- Precision placement on boards vs solder balls for flip chip connections
- I/O mirrors –edge mirrors polished in groups of 100's; within film mirrors achieved with excimer laser ablation
- Lens coupling for >100 micron gap connections
- 90 degree backplane to daughter board coupling with flex film
- Precision stacked arrays for 2D coupling interfaces
- Long runs interconnected via MT structures

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Functionality

- splitters, combiners, star couplers, crossovers, sensors, novel configurations-

Potential for GuideLink ™ Manufacturability – Production Scale Up

- **Formulations are stable** for nearly a year before and after coating providing reliable material source
- **High speed high volume production** with pre coated material in roll form using step and repeat or reel to reel processing
- **High speed laser precision micromachining** of self supporting films
- **Die cutting with vision assistance** for high speed part singulation
- **Processing in large groups** for exposures, micromachining, mirrors, metalization
- **Semi automated assembly** possible

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