Polymer waveguide technology: process, characteristics, general capability

Polymer waveguide attributes required for practical applications.

Critical attributes for a cost effective high performance polymeric waveguide optical interconnection system technology must be satisfied for practical applications to meet rigorous implementation requirements. These critical attributes for polymeric waveguide technology are listed in the attached table. They involve, for example, guide formation and performance, scalability for high volume manufacturing, connectorization, system application versatility, reliability, cost effectiveness and others .

OXL's unique polymer waveguide GuideLink™ system meets or exceeds these critical attribute requirements with a high level of performance and capability as summarized in the table for each attribute.

Technology maturity is assigned and rated for each important attribute using a scale of [1] to [4]; namely [1] literature, conceptual stage or early feasibility only, [2] laboratory demonstration, preliminary proof of concept, evaluation and testing, [3] prototypes constructed and delivered for evaluation, and/or demonstration or system design development, limited pilot production, initial application specific testing, [4] commercial product deployment, extensive testing, manufacturability demonstrated. Critical attributes in the table include all aspects of guide creation, connectorization, system and application performance, manufacturability, production costs, and capital costs.

Technology General Attribute	**Light induced self development –[3]**
Representative practitioners	Optical CrossLinks, Inc.
General process description	Pre coated photosensitive acrylate monomer &binder polymer on temporary carrier 1foot wide 100+ feet long. Contact photomask uv exposed waveguides. Monomer diffusion mass transfer creates higher density polymer guide. "Self-developed" guides are cladded with similar polymer, interdiffused, fully exposed, and bake cured. [3]
Effective CTE & Tg --- impacts Trunout,Tsolder reflow, and bonded substrate to flex link option	Robust outer layers w high Tg (>200C+) and low CTE <50ppm for T/mech prop.; permits IR reflow 300C 30 sec. [3]
Field size / tool size Volume production potential	Largest photomask exposure to date - 18x12 inches. Typical 6 in. [3] Direct write guides demonstrated, large mask or mask on rotating cylinder options for very long guides.
Optical loss	Bulk material, SM, and MM guides all same loss (no WG wall scatter) at 0.08 dB/cm at 840nm, 0.26dBcm at 980nm [3] System loss including connectivity is the key issue.
Guide size, index --range	4 to 100+ um sq. or rect. with 0.003 to 0.035 index to surround. Typical MM WG's 35x40um w NA ~.3 [3]
Density/pitch	MM guides with 4 micron space or greater. 10:1 hyperfine pitch Typical 50-200 um space. [3] Stacked for 2D arrays with 125 um vertical pitch in delivered product. [3]

Polymer Waveguide Technology: Connectivity

Technology Connectivity Attribute	Light induced self development –[3]
WG to/from VCSEL or PD's ---single or array	Film edge 45º I/O mirror (metalized) (~0.4dB loss) couple, precision within few microns both placement to solder balls and array runout [3] Stacked WG (4x12) array (+/-3um) to VCSEL arrays with butt coupling ferrule. [3]
WG to/from OF single or array ---loss impacted by overlap size variation and index profiles vs. GI OF	Direct butt / permanent or MT ferrule array [3] 0.5 to 1.5 dB WG to GI match dominates loss. Ferrule based on board edge or stand alone. [3]
WG to WG	MT ferrule based arrays [3] and permanent splices [3] also direct waveguide to fiber single and arrays.[3]
90º backplane to D board	Flex off substrate link with 5mm ROC and WG to WG couple for array connectivity. Single and dual layer guide MT style array connectors.[3] Blind mate/latchable housing with flex WG[1]
Embedded component in WG film	LD (edge) and filters (WDM)embedded in WG matrix [3] Embedded or ink jetted lenses –free space [1]
I/O mirror arbitrary location	Optional single or multi-guide I/O mirror location within film (not an edge) [2]. Pre cut film to locate I/O mirrors on boards vs fiducals or solder bumps[3] and metalized option for high NA[3] Internal 90 to 45 deg. mirrors constructed.[3]
Grating deflection in or out of plane	Imaged gratings for in plane [2],

Polymer Waveguide Technology: System Applications

Technology Applications Attribute	Light induced self development –[3]
	Optical signal routing with waveguide options for very high density to standard of 250 um pitch or larger
- point to point links	WG arrays for on board, flex jumpers, 90˚film bend links with 5mm ROC [3]
- crossovers	Low loss with internal guiding structure in crossover region [3]---complex routing link [2]
- lenses	Photoimaged cascade [3] or embedded for vias and free space links [1]
- mirrors	In and out of plane [3]
- splitters / combiners point to multi point or reverse	Standard tree branch (1x16) on board or self supporting connected & packaged with total excess loss <2dB at 850nm[3] or fan outs (1x 100) [3]
- distribution : multi-point to multi-point	Star couplers --tree branch format [3]
- WDM	MM filter insertion with internal guide structure [2]
- switches	MM bubble switch [2] Single mode phase change thermal demo'd with embedded Peltier control.[2]

Polymer Waveguide Technology: System Performance / Reliability Issues

Technology System Attribute	**Light induced self development –[3]**
System optical loss	Coupling interfaces losses particularly NA/size with step profile WG to graded index profile (GI) OF (typ. 0.5 to 1.5 dB) dominates over material/guide losses until lengths 20 cm or greater
Full Link System	Complete links Rx thru to Tx for 48WG arrays (4layer WG stacks 12WG per layer), 24WG arrays (2 layer stacks 12 per layer) delivered to customer site, 60 full set sof 48 array system in Beta test. All losses considered include: materials, guides, coupling VCSELto guide to fibers to guides to PD's, alignment, curvature (in plane imaged WG's and out of plane bent guide films), array position included as part of system loss. Typical Tx 1.5 dB±0.5 thru to Rx 2.3dB±0.5 for full link. [3] Other board level full links delivered with similar results and if mirror out of plane I/O an additional 0.3 dB typical for mirrors [3]
- IR solder reflow	Demo'd with no pitch or loss changes at 300C for 1 minute on board substrate [3]
- thermal cycling	Stable – 55 C to 125 C continuous cycling with repeatable no change in loss over every 2 hours cycle for months[3]
- time at temperature aging lifetime	Arrenhenius plot extrapolation---0.1dB/cm loss increase at 850 nm for 85 C for 5yr. and 10x less at 1300nm [3]
- 85 C / 85%RH	Protection if needed achieved with metalization, SiO2 coatings, packaging.[2] With no barrier protection stable no change in loss at 850nm until ~4 hours then increasing loss with polymer structure modification but loss reversible up to 24 hours, after 24 modification permanent; At 1300nm immediate loss increase but immediately reversible when moisture removed. All polymers absorb moisture under these conditions thus 1300nm, 1550nm will have higher loss due to absorbed moisture if measured during these operational conditions unless barrier layers are used.
- Coupling interface protection abrasion and solvents	Protected WG MT interface coupling 100 make/breaks with alcohol clean for each, no coupling loss increase [3]
Hermetic packaging	Packaging to block moisture from reaching solid state VCSELs, PD's etc and interconnecting waveguides inside packages with optical guide array going thru package wall under development [2]

Polymer Waveguide Technology: Manufacturability / Production Cost estimates

Technology Manufacturability Attribute	**Light induced self development –[3]**
Volume production	Manual WG films up to 5 sq ft per day –today [3] Reel to reel step and repeat (or cylinder roll) potential 10 to 100+ sq ft per day achievable
- machining /assembly	Precise machining is critical but slowest step for throughput [3] – needs semi automation, faster cuts low precision areas, pick and place operations. Other tools [2]
Cost estimates	Assumptions: 1) cost range given from low volume near term after production initiation with some fixturing &process improvements to higher vol. production with semi-automation out several years after production scale up , 2) assume reasonable hourly rates, All $ low to high volume after initial prod. manuf.
- polymer materials	Materials required to make finished WG film package, ~$40 to $20 per sq ft est. all layers
- waveguide imaging and processing for fully cladded and protected film structure	Costs ~several $100 per sq ft (batch size dependent); to ~$10 per sq ft with significant automation
- micro machining for connectivity, coupling, special structures & configurations	Depends on complexity with est. $500 to$1500 / sq ft. average for reasonable coupling and/or component size & density, using machine vision fiducals imaged during WG exp. to guide laser machining. High precision tools where needed, low precision low cost for general cuts. Mirrors and optical surfaces achieved with precision tooling.
-assemble/connectorize	Cost range based on assumptions above plus materials, processing, machining and assembly. Typ. coupling cost range: MT style conn. WG or Brd edge ~ $100 to $15 per unit with WG array. Brd to brd 90º $300 to $75 with internal WG array MT style connectivity and blind mate latch housing for MT's etc.
- protective / metal	Coatings for protection or for metalizing mirrors or electronic circuits ~ $800 per vendor run with many components processed per run so ~$2 each to higher $ for large (fewer) components
- testing	Needs automation, special designs for precision test fixtures (machine shop precision limitations on fixtures so precision upgrades needed). Estimates range from $75 to $5 per tested component with multiple guide arrays and coupling interfaces to fully test critical operating attributes

Polymer Waveguide Technology: Capital Equipment Cost best guestimates

Technology **Process step**	**Light induced self development –[3]**
Material preparation,	Vendor materials preparation using standard polymer processing chem. lab hoods and equipment like lab glassware, mixers, filters, pumps, solvent removal etc. Very batch size dependent, pilot scale [3] needs $15K; larger prod. volume $50K capital equipment needs
Material coating	Pilot scale needs met with lab bench coating onto temporary Mylar substrates using $2K equipment [3]. Production scale coatings $1M to $5M investment with coating, drying, large roll film handling, clean rm environment—typically using coating vendors like Rexam, DuPont etc.
Waveguide exposure and processing	Pilot scale low vol. production needs up to 10 sq.ft. per day per shift approx. $20K [3] including clean rm, air handling, exp box, film handling, ovens. Production volume of 100 sq.ft per day per shift ~ $300K investment, and 1000sq.ft. /day per shift $1M to $10M investment
Precision machining	Pilot scale low volume production precision machining and support $400K [3]. High prod. continuous process tooling, and multi cutting stages w different lasers and tool options ~$1.5M
Connectorization, Assembly, packaging	Pilot low vol. manual $10K equipment [3], low production with fixtures but manual $50K, semi-automated $500K
Lifetime, reliability testing	Extended testing, multi chambers continuous optical monitoring $200K to $1M potential
Optical testing	Standard array of testing, special fixtures data collection $500K [3]; lrg vol. production semi automated $1.5M
System testing	Electronics and Optical full system $500K dependent on complexity