ASSEMBLY

EXECUTIVE SUMMARY

This Roadmap is built around the Purple Brick Wall (PBW) concept that defines the PBW as the point in the future where known assembly processes are no longer have the cost-effective capability to fulfill the technical requirement defined by the PBW topic. Hence, near term capabilities to the left of the PBW are state of the art; requirements to the right in the future of the PBR are needs and somewhat speculative.

Before diving deeply into the chapter, we recommend studying the PBW chart in some detail.

This cycle of the Roadmap builds on the prior version published in 2020 by incorporating via Appendix A much of the still relevant state of the art detail described in that Roadmap, primarily in the section titled “Situational Analysis”.

The newly written material focuses on the longer-term technical barriers that the implementers of photonic technologies are likely to encounter that results from utilizing the Purple Brick Wall analysis to define unresolved needs. More specifically, this chapter on “assembly” addresses the issues related to joining and connecting different parts together to fabricate as an assembly or device. It is about methods to join parts with an emphasis on the methods required for the four types of modules the IPSR has defined as the focus for this Optical Roadmap cycle. (These four are Interconnect devices including transceivers, Optical Sensors, 3D Imaging Lidar, and Photonic RF.)

In addition, the chapter address assembly needs related to some specific items that are encountered in assembling devices that contain photonics and photonic integrate Circuits (PICs) including aligning to waveguides, joining optical components including PICs, providing thermal capabilities and high accuracy when appropriate, sealing part interfaces in cavities to control fluid flow of both gas and liquids as is important in biotech analytic devices. The utilization of additive fabrication (3D printing) and use of meta materials as an alternate to providing functionality by assembling parts is becoming viable and is addressed for solutions beyond the PBW for several needs.

Traditionally, the major cost and issue for assembly for reducing the cost of aligning single mode fiber to sources such as waveguides to PICs or optical components such as a ball lens. That alignment requirement is largely confined to interconnect devices and is now well understood and effectively addressed by experienced manufacturers. The alignment issue has minimal impact on sensors and 3D imaging as these devices do not usually utilize optical fiber.

Today’s assembly issues to the right of the PBW frequently relate to higher accuracy assembly or the meta and 3D printing methods that might be utilized to avoid assembly. They also include the issue of aligning sources, detectors and pigtails to multicore fiber that have 7 or more single mode cores in a single 125 micron outer diameter (OD) fiber.

Many of the longer-term needs require higher accuracy or higher precision so more information channels, higher signal-to-noise rations, etc., can be attained. A related final topic is solutions that require better materials and processes to provide better solutions and performance.

Introduction

The Assembly Chapter addresses issues related to putting parts together to make a final device, hence it is largely concerned with joining methods.

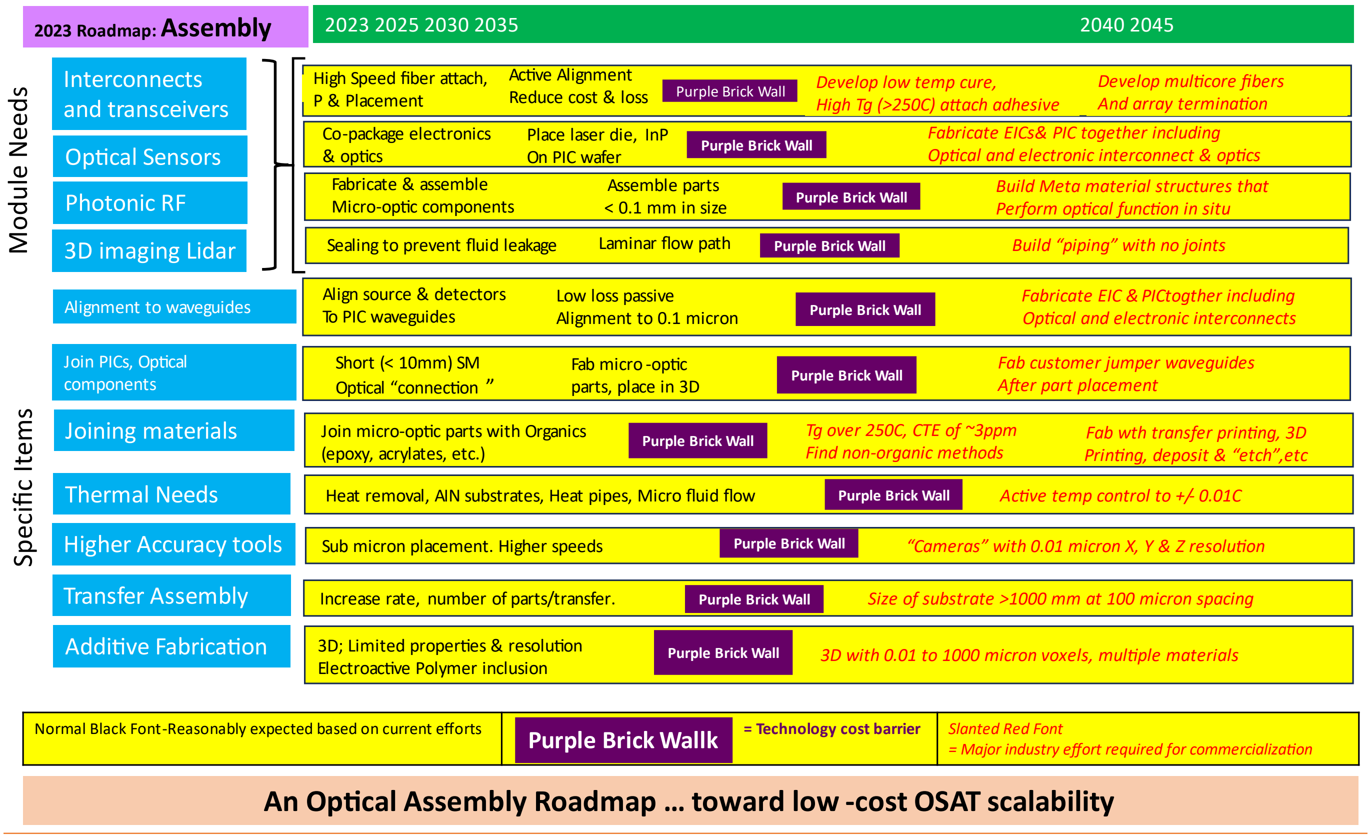
Optical assembly is currently about selecting bonding processes, adhesives, application methods and machinery to deposit joining materials (adhesives, solders, etc.), and then to cure or reflow them and characterize the final assembly with an emphasis on the joint.

In general, the basic assembly technologies used to build optical devices on a day-to-day basis are available and pretty well developed. Day-to-day engineering provides incremental improvements; customized variations are viable. Next generation devices (>2X improvement) require important change in some dimension. In the near term, meaning 5 to 10 years, existing processes can and will be improved incrementally to reduce cost and reduce losses, etc.

Long term improvement, meaning 10X, requires major innovation, hence the Purple Brick Wall that separates these two classes of improvement.

In the long run, major innovations are viable and will be implemented. The sections below elaborate on some of these technical possibilities. Whether or not the effort will be made to breach the Purple Brick Walls is unclear.

The Assembly Chapter Purple Brick Wall (PBW)



2023 Roadmap: Assembly 2023 2025 2030 2035 2040 2045

Module Needs
- Interconnects and transceivers
- Optical Sensors
- Photonic RF
- 3D imaging Lidar

High Speed fiber attach, P & Placement	Active Alignment Reduce cost & loss	Purple Brick Wall	*Develop low temp cure, High Tg (>250C) attach adhesive*	*Develop multicore fibers And array termination*
Co-package electronics & optics	Place laser die, InP On PIC wafer	Purple Brick Wall	*Fabricate EICs& PIC together including Optical and electronic interconnect & optics*	
Fabricate & assemble Micro-optic components	Assemble parts < 0.1 mm in size	Purple Brick Wall	*Build Meta material structures that Perform optical function in situ*	
Sealing to prevent fluid leakage	Laminar flow path	Purple Brick Wall	*Build "piping" with no joints*	

Specific Items

Alignment to waveguides	Align source & detectors To PIC waveguides	Low loss passive Alignment to 0.1 micron	Purple Brick Wall	*Fabricate EIC & PICtogther including Optical and electronic interconnects*
Join PICs, Optical components	Short (< 10mm) SM Optical "connection"	Fab micro-optic parts, place in 3D	Purple Brick Wall	*Fab customer jumper waveguides After part placement*
Joining materials	Join micro-optic parts with Organics (epoxy, acrylates, etc.)	Purple Brick Wall	*Tg over 250C, CTE of ~3ppm Find non-organic methods*	*Fab wth transfer printing, 3D Printing, deposit & "etch",etc*
Thermal Needs	Heat removal, AlN substrates, Heat pipes, Micro fluid flow	Purple Brick Wall	*Active temp control to +/- 0.01C*	
Higher Accuracy tools	Sub micron placement. Higher speeds	Purple Brick Wall	*"Cameras" with 0.01 micron X, Y & Z resolution*	
Transfer Assembly	Increase rate, number of parts/transfer.	Purple Brick Wall	*Size of substrate >1000 mm at 100 micron spacing*	
Additive Fabrication	3D; Limited properties & resolution Electroactive Polymer inclusion	Purple Brick Wall	*3D with 0.01 to 1000 micron voxels, multiple materials*	

Normal Black Font-Reasonably expected based on current efforts	**Purple Brick Wallk** = Technology cost barrier	*Slanted Red Font = Major industry effort required for commercialization*

An Optical Assembly Roadmap … toward low -cost OSAT scalability

Figure 1. *Assembly Chapter Purple Brick Wall*

This IPSR Roadmap focuses on 4 groups of Modules, so this graphic and this Assembly Chapter are organized around those Modules; Interconnect including transceivers, 3D Imaging, Sensors and RF Photonics.

The PBW graphic has rows split into two groups.

The first 4 rows are generally applicable to the 4 module types the IPSR addresses. The interconnect devices are those that require single mode fiber alignment, the single most important assembly process in optical electronics due to its high cost compared to other processes.

The bottom 7 rows are applicable more broadly to not only the modules addressed by IPSR but other optical applications as well.

Study the PBW graphic before reading the following material This material addresses the current technology and trends that represent the near-term status of technology to the left of the PBW in black text as well as the more speculative and longer-term possibilities to the right of the PBW in red text.

SOME MODULE EXAMPLES

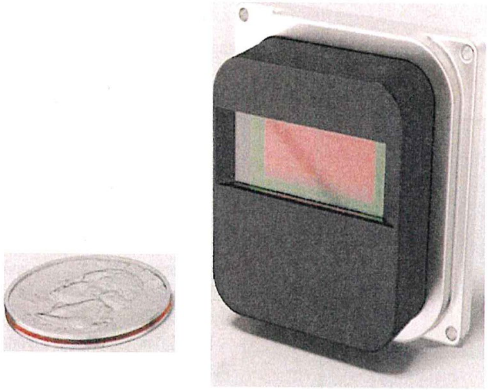
This image is from a recent Intel announcement. It illustrates the trend toward co-packaged optics. Note the multiple fiber arrays exiting from two sides of the primary device housing providing 10’s of terabits/sec of IO capacity. This is an example of the types of devices that we need to assemble.

Another set of examples of devices that will be assembled are those from Analogue Photonics in the images on the right. Exactly what is inside of these devices and the detailed assembly issue that are encountered are rapidly emerging.

These renderings show what the lidar models now in development are anticipated to look like. The one on the left is designed for long range with a narrow field of view, whereas the one on the right will operate at short range with a wide field of view. ANALOG PHOTONICS

Finally, another Lidar concept that is even smaller Illustrating the benefits of utilizing Photonic Integrated Circuits to build a Lidar device.

Chip-Scale Lidar



Miniaturization and integration are key to the automotive industry's aim to incorporate lidar into vehicles on a broader scale. Leveraging silicon photonics technology will be critical to that aim.

ASSEMBLY PROCESSES

Module Assembly Needs

The table below lists these Modules along with the needed key assembly processes. The number of X's in a box indicates the importance of that process to that module.

	Assembly Technology Needs										29-Oct-23	
Modules	**fiber to edge emitter**	**fiber array to edge emitter**	**fiber in V groove**	**fiber to PIC**	**fiber array to PIC**	**fiber to vertical emitter/ detector**	**micro optical components; lenses, mirrors, prisms, gratings, etc.**	**High IO (>100) PIC to electronic die**	**Laser die attach to PIC**	**Detector die attach to PIC**	**Temp control, heat dissipation**	**Fluid seal**
Interconnects (Transceivers)	x	x	xx	x	xxx	x	x		xxx	xx		
3D Imaging								xxx	xxx	xx	xxx	
Spectroscopy & refractive index sensing	x		x	x	x		xxx	x	xx	x		xx
RFPhotonics	x	x				x				xx	xx	

Key metrics

The Key metrics for optical device assembly depend on the device; these Key metrics fall into these categories;

1. Cost:
- $/device built
- $/active fiber aligned
- $/part joined
- $/hr of assembly labor,
- $/kilo for materials, etc.
- $/KWh
- Assy cost vs material cost

2. Throughput
- Units/hour
- Yield
- Number of parts
- Number of assembly steps

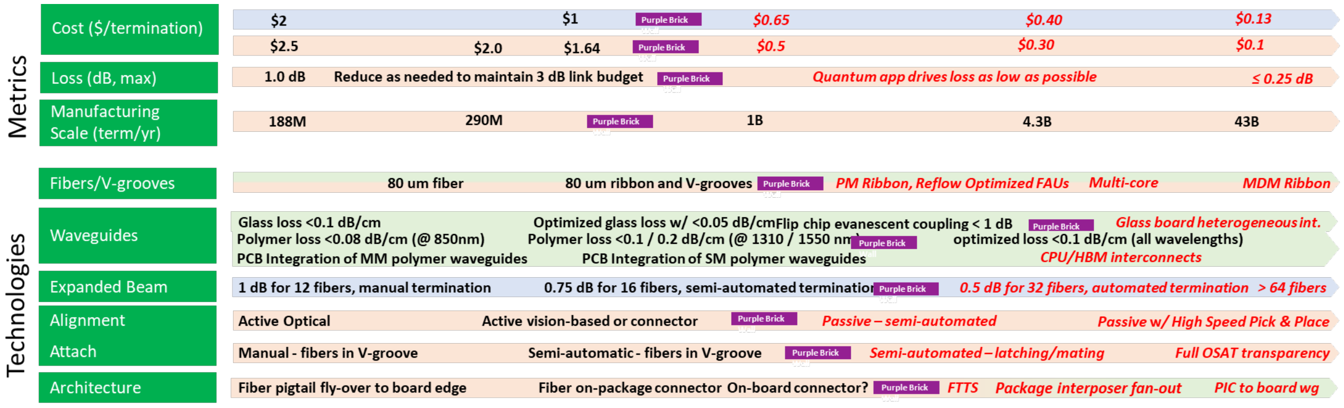
3. Light coupling loss per joint
- db per fiber to Laser or detector
- db per fiber to fiber
- db per fiber to waveguide
- etc.

4. Performance Technical parameters
- % Optical frequency shift per degree C change
- db of loss increase per degree C change
- db of loss per % humidity increase
- Thermal resistance
- Joint strength
- Thermal dissipation/unit area

The major trends in these parameters are well known;

- 25 to 50%/yr increase in data transmitted/yr.
- continual reduction in joules/bit communicated
- more data per mm and mm^2,
- more cores per fiber,
- more bits/cycle of bandwidth,
- lower cost per bit transmitted
- etc.

The below extract from the Interconnect PBW graphic provides details on the metrics for those devices (primarily transceivers) that need to be achieved by the assembly processes.



Metrics	Cost ($/termination)	$2 $1 Purple Brick *$0.65* *$0.40* *$0.13*
		$2.5 $2.0 $1.64 Purple Brick *$0.5* *$0.30* *$0.1*
	Loss (dB, max)	1.0 dB Reduce as needed to maintain 3 dB link budget Purple Brick *Quantum app drives loss as low as possible* *≤ 0.25 dB*
	Manufacturing Scale (term/yr)	188M 290M Purple Brick 1B 4.3B 43B
Technologies	Fibers/V-grooves	80 um fiber 80 um ribbon and V-grooves Purple Brick *PM Ribbon, Reflow Optimized FAUs* *Multi-core* *MDM Ribbon*
	Waveguides	Glass loss <0.1 dB/cm Optimized glass loss w/ <0.05 dB/cmFlip chip evanescent coupling < 1 dB Purple Brick *Glass board heterogeneous int.* Polymer loss <0.08 dB/cm (@ 850nm) Polymer loss <0.1 / 0.2 dB/cm (@ 1310 / 1550 nm) Purple Brick optimized loss <0.1 dB/cm (all wavelengths) PCB Integration of MM polymer waveguides PCB Integration of SM polymer waveguides *CPU/HBM interconnects*
	Expanded Beam	1 dB for 12 fibers, manual termination 0.75 dB for 16 fibers, semi-automated termination Purple Brick *0.5 dB for 32 fibers, automated termination* *> 64 fibers*
	Alignment	Active Optical Active vision-based or connector Purple Brick *Passive – semi-automated* *Passive w/ High Speed Pick & Place*
	Attach	Manual - fibers in V-groove Semi-automatic - fibers in V-groove Purple Brick *Semi-automated – latching/mating* *Full OSAT transparency*
	Architecture	Fiber pigtail fly-over to board edge Fiber on-package connector On-board connector? Purple Brick *FTTS* *Package interposer fan-out* *PIC to board wg*

The graphic illustrates that metrics for a specific module (interconnect, 3D imaging, Sensors and RF) depend on the design and packaging of those types of devices.

Technology needs

The most important current assembly cost issue is the cost to align single mode fiber to sources and detectors and fasten the fiber in-place so they are stable over the life of the device. Much effort, time and investment has been made to fill this need in recent years resulting in well developed processes producing high volumes (millions per year) of devices. These current processes are reaching the limit of their technical capability with cost reduction rates slowing if not stabilizing.

However. to other parameters can be optimized to reduce cost and improve performance. These efforts include better materials that are stable over longer lifetimes, more accurate assembly processes that reduce variation not only at the time of assembly but over the operational life of the device. These improvements manifest themselves as lower power, more bits/sec, more bits/mm etc.

A continuing near term need is for better performance and lower cost for devices built in small volume (1000s per year) without major investments in process development. An alternative to achieve this is standardization, which is emerging slowly along with continuous improvement in materials, equipment and processes.

Some of the improvements needed for assembly of the broader range of optical devices, beyond those that require fiber alignment include:

Material Systems

Organic optical joining materials that “cure” quickly at low temp (<85C) and remain rigid at high temperatures (250C) are needed. Available materials are marginal in performance; the needs are for higher temperature tolerance meaning less modulus reduction, less increase in CTE, higher glass transition temperature, Tg (or even elimination of that phase change) less deterioration in modules, elongation (less brittle) and lower loss as these organics age.

Ideally all of the materials for optical system parts would have a similar CTE; transmission media such as fiber or lenses, semiconductor sources and detectors, the substrates for mounting parts, electronic conductors, providing thermal control and environmental protection, and lastly joining materials. Ideally all of these would have very similar CTEs meaning within 1 ppm/C over an operating range of about -40C to + 125C. These ideal goals are not likely to be achieved but steps toward them are part of the continuous improvement that should continue.

Additive Manufacturing

Two types of additive manufacturing are currently used.

The first is that used to build semiconductors by depositing, patterning and removal of unwanted material by a layer approach 2 nm resolution. This technology is currently being used to fabricate multiple devices well beyond semiconductor devices, including optical devices and a variety of small parts that require high accuracy. Little more need be said here as the use of these technologies is widely discussed.

The second additive method is 3D printing. This technology has the potential to revolutionize manufacturing, especially small devices. In addition to current capability, 3D printing needs to develop the following capabilities.

1. Voxel size: methods of making voxels from relatively large sizes like 1 mm3 to submicron, meaning 0.001 micron3, are needed to build optical parts and devices. The small size is required if individual voxels are to be deposited to form a reflective surface. This ratio of 100,000:1 is compounded when voxel volume is considered to 10^{+15}. Again, we face a PBW that is quite severe. How this need might be filled is unclear.

2. Another 3D need is to deposit multiple materials in a device. That will enable fabricating many more devices. Depositing materials with 2 different indices of refraction, for example, will, in principle enable building optical structures. (See the following section on meta materials.)

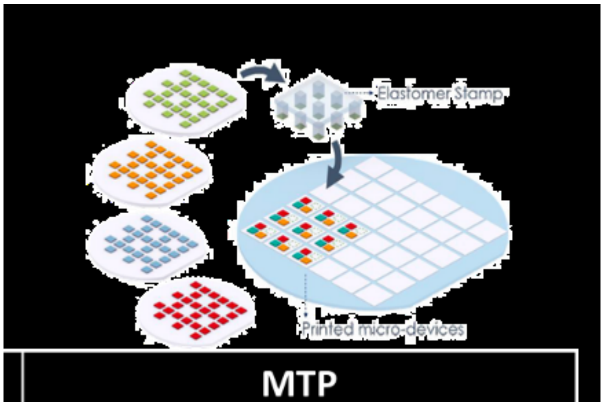
3. In addition electronic conductors might be added to build opto-electronic devices.

These first two needs are difficult to achieve; doing so requires breaching the PBWs. Realistically technology will move incrementally toward these capabilities as opportunities present themselves. Surpassing the PBWs will occur only when the benefits of doing so are clear enough that the considerable level of resources needed will be made available from some organization or firm.

Transfer Assembly

Transfer assembly, or transfer printing as it is commonly called, is an emerging process. It is an expansion and variation of classic pick and place assembly. Multiple die are picked up at the same time with a large tool and simultaneously placed on a substrate at once. Die from different source wafers can be placed and intermixed on the same substrate/device.

The process is attractive for building large arrays (1000s x 1000s) of sources (red, blue green, micro- LEDs) for displays or detectors. Displays using die as small as 50 microns square paced on 100-micron pitch are in development



Multi die Transfer assembly concept.

The process requires compatibility of the source die wafer spacing with the needed substrate die spacing implying coordination of wafer fabrication and substrate/target device design.

Once the die are placed, they must be electrically connected, another process that requires highly accurate processes and related tools and materials. See Appendix C for more complete information on transfer assembly.

Assembly Tool Needs

Assembly tools, meaning tools that pick up individual parts and place them on a substrate or in a specific location with respect to another part are well developed for planar 2-dimensional requirements. Accuracy of less than 1 micron is attainable. That limit results from utilizing optical cameras with their resolution of ~ 1 wavelength of visible light to monitor part locations during placement. What is needed for higher accuracy is cameras with higher resolution. That implies electron beam or X-ray technology that requires major investment. This is not a new idea but the investment has not been made hence it is a “Higher Accuracy Tool PBW”

Another emerging assembly tool need is for equipment to implement “transfer assembly” described above in which multiple die are picked at the same time. The necessary tool will eventually need to handle large panels for display implying multi-meter dimensions, with part to part/die location accuracy of 10 microns or less. See further information on transfer assembly in appendix C.

A final tool need is for equipment to implement 2 photon polymerization used to fabricate optical waveguides and meta materials in-situ. See Appendix D for more information.

The Future of Assembly

Assembly can be viewed as an unnecessary step. An alternative that is emerging and may dominate the future is fabricating parts in-situ rather than fabricating them as individual pieces and assembling them. 3D printing is this type of process as it produces near complete parts without machining. In principle, 3D printing can be used to build complex devices in the 3rd dimension if it can deposit the right materials with the right dimensions and the right properties needed. See the discussion regarding “Meta Materials” in “Recommended Alternate Technologies” below.

Artificial Intelligence is impacting manufacturing by enhancing the ability of device and process engineers to optimize designs and processes by simply making more options easily known and available.

A similar and related long term trend affecting manufacturing, including optical assembly, is computer aided process design. The entire assembly sequence including joining processes is simulated in detail. Rather than make all of the parts and then develop an assembly process using “trial and error” for each step as is common with epoxies, acrylates and solders, the assembly tools, joining materials (solder, epoxy acrylates, etc.), and joining processes are simulated by computer to ensure they will work when implemented with real parts, materials and tools. As devices become smaller, variation less tolerable, tooling more expensive and multiple devices are incorporated utilizing heterogeneous assembly, the benefits of simulation increase.

Critical infrastructure issues

Incremental improvement

Continual incremental improvement of existing technologies is the most critical infrastructure issue. Small improvements add up to provide most technical improvement in both performance and cost. This process requires cooperation and working together up and down the research, development, vendor, manufacturing and end user chain, something at which the industry is very adapt. Innovation often starts in Universities resulting in spin outs that merge with commercial interests and form startups that pioneer improvements.

Once a new technology is proven, mainstream component and system suppliers acquire these small firms, integrate their technology into their product lines, make the investments to further reduce cost and then proliferate the capability widely. This process built the communication system we have today and it continues contributing to the advancement and proliferation of optical and other technologies. ***We should understand, support and continue utilizing this key infrastructure development process.***

Assembly technology benefits from this process in the form of new materials, processes and machines that continue to emerge and enhance optical system performance.

Major improvements

In addition to incremental improvements, major leaps and advances sometimes occur and rapidly result in enormous improvement. Optical fiber replacing electric communications is an example. Transistors replacing vacuum tubes is another. The Purple Brick Walls in the IPSR graphics sometimes highlight potential major leaps that can be envisioned. Whether or not the PBW is "breached" by developing and implementing the improvement is a complex infrastructure issue.

Near term Assembly Infrastructure Needs

Many of the current technologies (CMOS electronics, SM fiber, active alignment, etc.) are reaching the asymptote of their performance with further improvements increasingly expensive. We need further innovation in multiple dimensions.

The major assembly related infrastructure needs will result in:

- Continual improvement in performance meaning:
- More bits/second
- More bits/watt
- More bits per mm or mm^2
- More bits/$
- Less variation and loss increase
  - with temperature
  - over time

Two key areas of improvement are these:

- Better tools
- With submicron alignment capability
- Able to work at faster rates
- Able to assemble smaller parts
- Better non-metallic joining materials
- Low temperature curing to a "high" modulus
- High temperature tolerance i.e. 85C, 125C. etc. as required
  - Tolerate the 250C reflow process
  - Less aging meaning change of key properties
  - No yellowing, embrittlement, or dimensional changes"

These improvements will occur as effort is expended by someone with the interest and resources to develop the materials, demonstrate their performance, then make them available.

Infrastructure Stability

A contemporary issue is geographic concentration of assembly services for not only optical devices but manufacturing in general. Actual and/or potential disruption of this international system has become a source of concern with efforts to provide backups and alternate sources underway. How these trends will "play out" is unclear. In the interim they are causing much discussion, proposed alternatives, cost analysis and investment.

Recommendations on Potential Alternative Technologies

Alternate Semiconductors

Optical technology would benefit by moving from silicon-based CMOS electronics with its 28 GHz upper frequency limit to higher speed technologies meaning SiGe, InP or GaAs. Cost effective methods to build chips with these materials needs to be developed further so the improvements in performance they enable are available.

This might be done by adding other materials to conventional CMOS utilizing heterogeneous integration. (See reference 9.) Alternately this might be done by developing the technologies to make high transistor count devices in those materials. Today the cost of those materials is much higher than CMOS making it unattractive to use them in high volume applications like transceivers. This is a Purple Brick Wall.

Emerging Optical Waveguides & Methods

Another trend is toward more parallel communication channels, meaning 32 up to 2048 and higher. Multi-channel arrays of fibers, sources and detectors will enable parallel handling to reduce cost and increase density.

Multi core optical fiber, meaning 7, 16, 25, etc, single mode (SM) channels in one cladding, is an attractive direction due to the density and parallel handling benefits.

Multi core fiber for long haul telecommunications, where the physical size of the transmit and receive components is not important, is viable now. The next step will be reducing the size and cost of the transmit/receive devices by utilizing photonic integrated circuits so they can be used in data centers, within racks, within trays and in packages. This technology, the associated light sources and detectors, need to be developed along with the assembly methods which is another Purple Brick Wall.

Two photon enabled polymerization has been used to form waveguides in solids, like glass, and in liquids by polymerizing the liquid then draining off the remaining liquid. This is a potential technology that might be developed further to provide optical connections, especially for PIC to PIC, PIC to die, PIC to waveguide, etc. is another Purple Brick Wall.

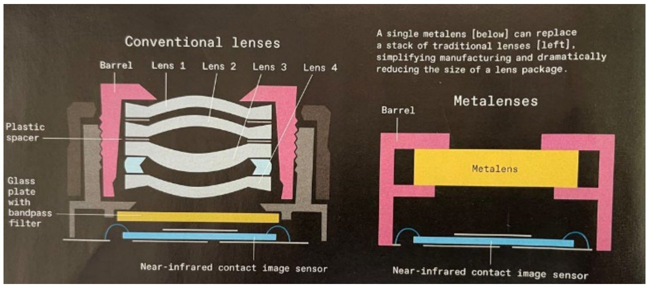
Some technologies beyond the PBW in that graphic require/propose 3D printing, deposition methods and laser forming methods. All of these have in common an approach to building devices by adding materials by depositing it rather than by adding an individual part joined with an adhesive.

Thermal Control Needs

Thermal Control is growing in importance as the optical data rates increase and new applications, like sensing and LIDAR, require greater control of optical frequencies. Note that 1 part per million/°C (ppm) of variation in the 200 THz/s visible optical band is 200 MHz. Hence, a 1GHz variation easily results. The point is that temperature control to a fraction of a degree C is likely to be key to the success of some optically enabled devices. Another Purple Brick Wall.

Meta Material Devices

Meta structures are a class of component with much potential to reduce size and add functionality in a small space. These devices potentially offer greatly increased and new functionality so their use is likely to increase greatly over the next few decades. Methods of designing and characterizing these complex geometrical structures are emerging.



A single metalens [below] can replace a stack of traditional lenses [left], simplifying manufacturing and dramatically reducing the size of a lens package.

The image to the right is an example of a complex classic lens whose functions can be replaced by a meta surface in multiple applications.

What is needed is the development and proliferation of practical functional meta devices. Ideally a "catalogue" of meta devices will emerge. Each device will have a design guide specifying its optical functions, the necessary geometric structure and material properties. With this catalogue, engineers can begin considering the use of meta devices. Ideally, these meta components will become available in the market, presumably from specialized fabricators.

Gratings and grating couplers are a basic type of meta surface. In addition to 2D meta surfaces, 3D meta structures are possible. Hence, design methods are needed as well as methods to fabricate them. Some of the possibilities are listed in the table below.

Meta Structure Hierarchy

Type	Geometry	Functionality	Comment
Grating	Series of lines equally spaced		Well known
Grating coupler	Series of lines in a teardrop pattern	Fiber to PIC interface	Some use in PICs
3D solids made with a high index transparent material in air	Surfaces in 3 dimensions	Replace classic optical chain	Viable in concept. Need method to build.
3D solids made with multiple transparent materials with varied indices of refraction.	Complex surfaces	High functionality	Also need design method.

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David Gomez	x-Celeprint	
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J. van Kerkhof	Joost & PHIX	
Ruggero Loi	x-Celeprint	
Dick Otte	Promex Industries Inc.	Co-Chair
Yi Qian	Mycronic	Co-Chair
Bradley Snyder	phix photonic assembly	
Irving Wang	Mycronic	

APPENDICES

A. Link to the Assembly Chapter of the 2020 Roadmap

B. Situational analysis

Design priorities for assembly

To minimize cost, reduce complexity and maximize reliability, designers utilize the following priorities.

1. Minimize assembly by minimizing the number of parts when viable.
2. Once part count is minimized, minimize the number of different joining steps and processes required.
3. Minimize the time needed to do the assembly.
4. Next, minimize amount of material consumed in the processes.
5. Maximize the quality meaning less than 0.1% defective parts.

Standards

This need is well recognized and very broad in optical devices and continually developing for multiple optical topics including assembly. Within assembly, some basic standards have emerged especially for basic fiber. Beyond that, standards are emerging.

Supply Chain

In recent years, geopolitical stability has become an issue for manufacturers resulting in not only costs in the form of tariffs and fees but other more complex restrictions as well.

C. Micro Transfer Printing

D. Nanoscribe 3D printing

E. References

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