POLYMER MATERIALS

EXECUTIVE SUMMARY

Technology platform

Polymer (organic) based technologies for optoelectronic and photonic applications have been developed by both academia and industry over the past 40+ years and are currently in the process of commercialization with the first announcements of active polymers occurring in 2023.

Both active and passive polymers have been commercialized and made into products by several companies globally. The key applications for photonic based active electro-optic polymers are fiber optic communications, namely telecommunications, data communications, high performance computing, where fiber optic interconnects and links are utilized. The key applications for passive polymers such as polymer waveguides, plastic optical fiber, and two photon polymermization (TPP) are fiber optic communications, automotive, medical, display, and consumer.

Current platform status

The whole industry today (material vendors, semiconductor foundries, various chip suppliers, standards organization, test equipment vendors, package houses) are growing their business for line rates of 100G, and gearing up for line rates of 200G. These line rates are being used to generate products such as the optical pluggable transceiver for aggregate data rates of 400Gbps, 800Gbps, 1600Gbps (or 1.6Tbps), 3200Gbps, 6400Gbps and beyond. While companies are looking to complete the designs for 200G line rates in 2023-2024 timeframe, they are also looking how to extend the data rates and line rates further. Interest in line rates of 300G and 400G are still at an early stage, however, active electro-optic polymers offer modulator device demonstrations today that achieve these goals. Passive polymers and POF will be able to support these extended line rates with waveguides and interface coupling components as part of a subsrate platform. Commercializaiton of these performance metrics by both active and passive polymers is expected over the next decade.

The obvious, yet most difficult next move for device designers of modulators is to revisit increasing the optoelectronic device speed as semiconductor solutions are stuggling to achieve the bandwidth, low power and small size needed for the markets. Active electro-optic polymers can exceed the semiconductor incumbent modualtors by nearly an order of magnitude on 3dB bandwidth as well as power consumption with sub 1V operation. While incumbent semiconductor modulators are operating fiber optic communications traffic with optical 3dB bandwidths in the range of 30-40 GHz (to generated data speeds of 50Gbps NRZ and 100GBaud PAM4), active electro-optic polymer modulators have demonstrated optical 3dB bandwidths that are in excess of 250GHz using plasmonic slot designs[1], and silicon slot modulators similarly with over 100GHz[2].

Further, speed is not the only issue for modulators: low power and size are also important. The demands by datacenter designers to lower power consumption and maximize space efficiency are critical metrics for the architecture. The good news is that active electro-optic polymer slot modulators[3] either plasmonic or silicon slot are very small in footprint with less than one square millimeter. As part of a PIC platform, many modulators can be arrayed subject to the architecture design of for example: 4 lane, 8 lane, 16 lane PIC designs. Active electro-optic polymer slots have been demonstrated to operate with very low voltage levels of less than 1V

[1] ETH Zurich, Polariton, CA?U University Kiel, EU Horizon 2020, LWLG
[2] Polariton, ETH Zurich, LWLG
[3] Traditional polymer optical slot modulator application as designed for example from Polariton, LWLG

(which means that the modulators themselves not only save power but can be directly driven by normal electronics and thereby eliminiating the driver chips). The potential elimination of driver chips means that the architectures save more power than the modulator itself – which is a strong differential advantage for low power designs. When these performance metrics of low power and small size footprint are added to the natural high optical bandwsith of modulators designed with active electro-optic polymers, commercialization opportunities look extremely promising over the next decade.

Today's roadmaps are demanding photonic components with increased performance. With the latest results from seminconductor modulators stretching to operate at 50-70GHz, while suffering higher drive voltage, the need for 100GHz bandwidth solutions to achieve 100G, 200G line rates with cleaner optics is increasing. Already, companies are looking at lowering power consumption in datacenter switches and routers by eliminating the DSP chip and directly driving the optics from ASIC switch chips. While this movement is still at an early stage, the network system architects are looks creatively to save power consumption both from the electronics as well as the optics. Faster optics, i.e., cleaner signals for NRZ, PAM4 using higher bandwidth optical modulators, operating with sub 1V voltage levels for lower power consumption is quickly becoming key for next generation optical network systems.

Unlike conventional modulator materials such as InP, Lithium Niobate, silicon photonics and GaAs, the polymer material system is naturally fast. There are now companies that are commercially designing commercial high-speed optical modulators made from electro-optic polymers that will be capable of line rates of 200G beyond using either discrete modulators or arrayed modulators in a PIC with 3dB bandwdiths that easily exceed 70GHz and can range up to 250GHz.

Several commercial companies have been able to prove the maturity of planar polymer waveguides for passive light guiding. The polymers provide low loss and further good optical quality to enable fast optical signaling on-board and board-board via optical backplanes. The availability of single-mode polymer waveguides to support cost-effective pluggable optical transceiver packages as well as co-packaged platforms with and enables PIC platforms such as silicon photonics.

In polymer based optical fibers (known as polymer optical fiber (POF), optical attenuation is a key metric, and recent maturity in terms of dB/km is enabling short distance interconnects to be designed with low cost for volume consumer markets. While POF is larger in diameter to glass fibers, it does not need to be cleaved, and can be installed quickly and maintained efficiently for small networking environments.

PURPLE BRICK WALL

The polymer roadmap that displays the purple brick walls is shown below in Figure 1 and Figure 2. The first figure shows the individual line purple brick walls for each technology segment. The following figure shows the purple brick wall areas that require focus to addesss the challenges in order to achieve the metrics laid out in the polymer roadmap.

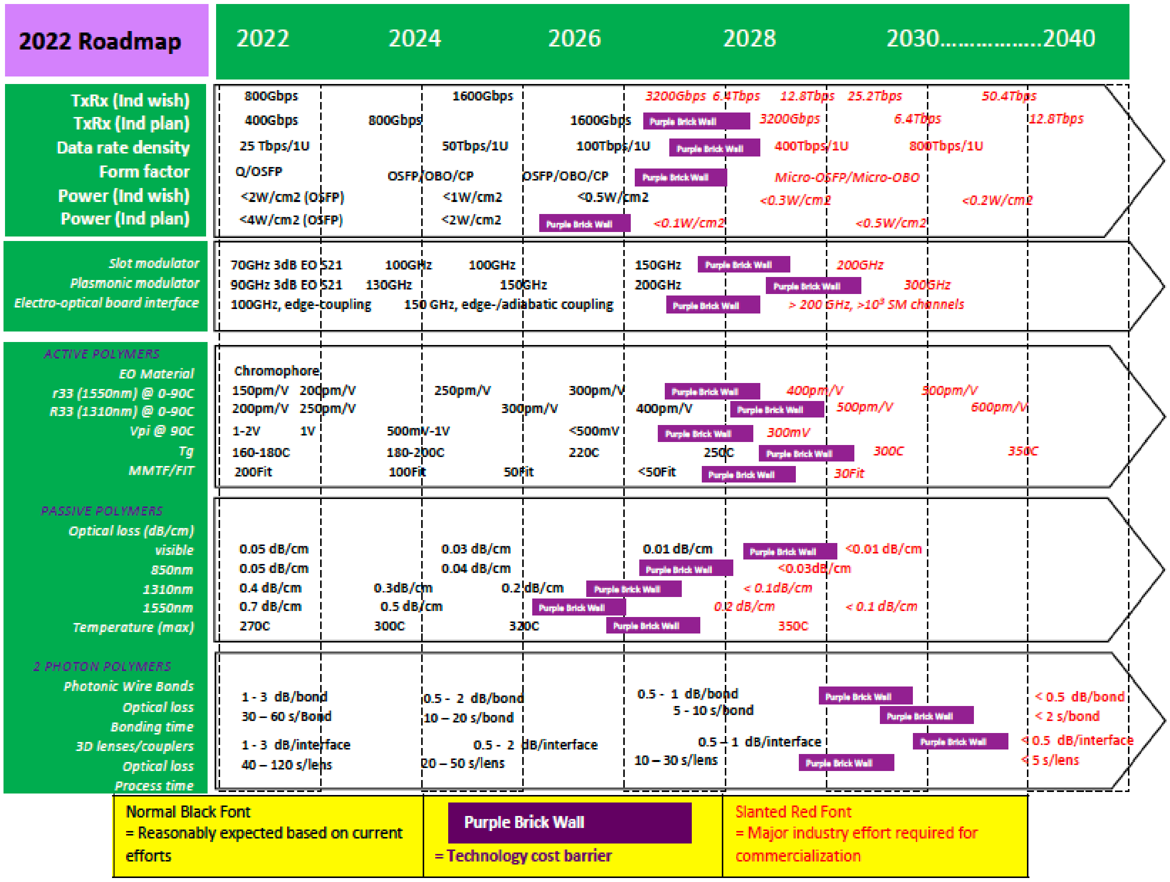

Figure 1: Polymer roadmap showing purple brick walls for three technology segments (Source: LWLG, Vario-Optics, Vanguard Automation, Polariton)

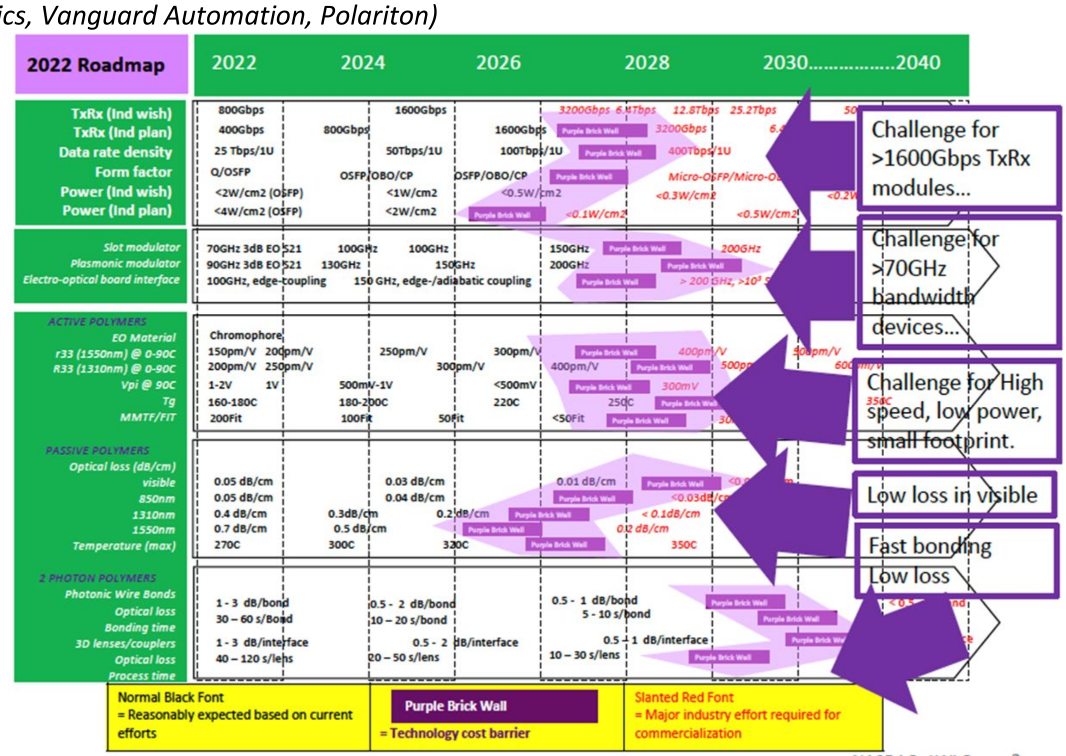

Figure 2: Polymer roadmap showing the key challenges identified by the purple brick walls for three technology segments (Source: LWLG, Vario-Optics, Vanguard Automation, Polariton)

Table 1. *Purple brick wall barriers – critical needs for polymers*

Purple Brick Wall	Description
Product vehicle	>3.2Tbps optical transceiver
Polymer device (modulator)	>150GHz 3dB bandwidth (for 100Gbps NRZ; 200G PAM4)
EO material	>400pm/V
Voltage drive	<1 Volt
Manufacturing Scale	Foundry to fabricate PICs onto silicon photonics/wafers
Waveguide loss	Low loss in visible wavelengths <0.01dB/cm
Passive polymer temperature	>350C for automated assembly techniques
TPP wire bonds	<0.5dB/bond
TPP lenses/couplers	<0.5dB/interface

Main Roadmap Challenge

The main roadmap challenge for the communications industry is to plan future data line rates that exceed 200G and extend towards 300G and 400G. These line rates are needed to achieve pluggable transceiver and/or co-packaged transceiver aggregate data rates of 400Gbps, 800Gbps, 1600Gbps (or 1.6Tbps), 3200Gbps, 6400Gbps and beyond. While companies are looking to complete the designs for 200G line rates in 2023-2024 timeframe, they are also looking how to extend the data rates and line rates further[4]. Interest in line rates of 300G and 400G are still at an early stage, however, active electro-optic polymers offer modulator device demonstrations today that achieve these goals.

Several vendors are looking at how to address 200G line rates, and are planning spatial multimplexing (adding fibers), wavelength division multiplexing, (adding wavelengths in a single fiber), encoding with more complex symbols per bit (PAM, QAM etc), designing optical and electrical devices for higher bandwidth, lower voltage (power), and smaller footprint (size) as part of a PIC platform. These higher performance drivers are being accelerated by data hungry customers such as data centers, high performance computing, and shorter reach telecommuications. Figure 3 below shows the trends in optical pluggable transceivers for the data communications market and range out to 3.2Tbps using 16 channels and 200G line rates.

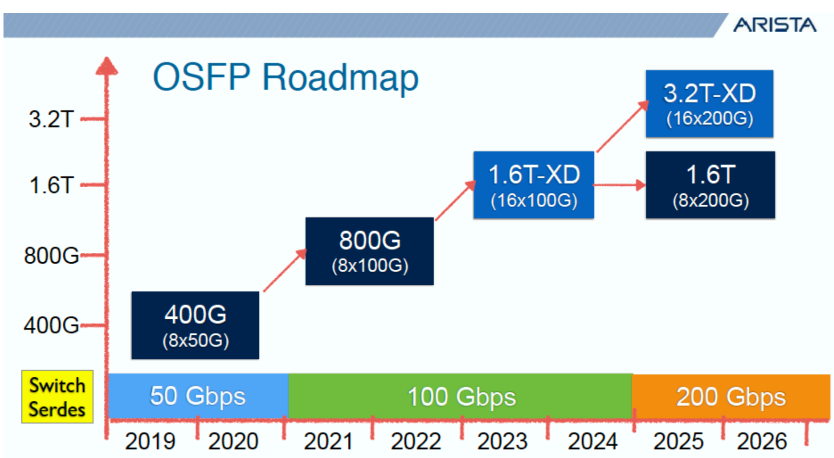

Figure 3: OSFP roadmap showing the increased trends in data rates for optical pluggable transceivers for datacommunications. (Source: Arista (OFC 2022))

[4] Arista presentation from OFC 2022 for OSFP pluggable optical transceivers

A particularly difficult challenge is to increase an optical device's analog bandwidth to that beyond 100GHz, while keeping the power consumption very low. This is further made complex as the modulation signal will need to be driven with similar data rates electronically from electronic drivers for the transmitter, and received by associated detection circuitry, transimpedance amplifiers etc., at the receive end of the optical interconnect. With the drive in 2023 to potentially eliminate the DSP chip[5], network archtiects are not only looking to polymers for the optical solution, but to combine cleaner, faster polymer optics with more power efficient electronic designs called Linear Drive Optics (LDO) that potentially could drive the optics directly from ASIC switch chips as opposed to DSP and driver chips. Figure 4 below shows the perspective from a network systems company that is looking to implement LDO to save not only cost but power consumption in the network.

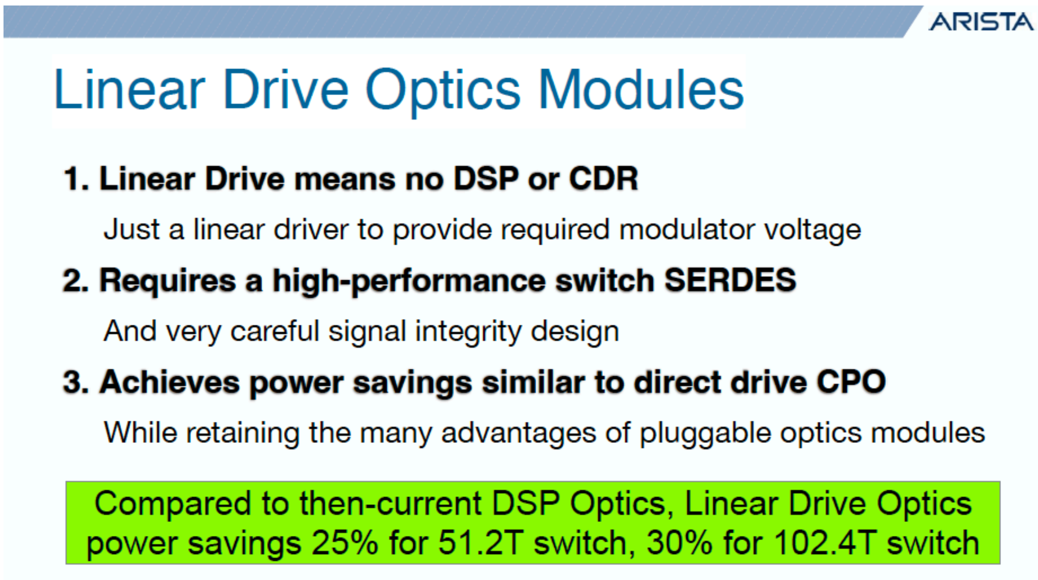

Figure 4: Network systems company Arista's comments to claim that eliminating electronic ICs is possible to reduce power consumption in network system equipment (Source: Arista (OFC 2023))

TECHNOLOGY FORECAST OF ELECTRO-OPTIC POLYMERS

In the field of active electro-optic polymers, there has been significant technological and commercial progress. There are now commercial companies that are supplying active electrop-optic polymer material as well as commercial companies supplying silicon slot and plasmonic slot modulator devices, and devices embedded into photonic integrated circuit (PIC) platforms.

With the natural ability for active elctro-optic polymers to be operated at very fast optical switching and become part of the popular trend of design PIC based solutions, optical devices such as modulators have the potential to drive this market opportunity quickly over the next decade.

The performance of electro-optic active polymers in the last few years has been incredible[6]. While incumbent semiconductor modulators are operating fiber optic communications traffic with optical 3dB bandwidths in the range of 30-40 GHz (to generated data speeds of 50Gbps NRZ and 100GBaud PAM4), active electro-optic polymer modulators have exceeded these bandwidths by an order of magnitude. Plasmonic slot modulators have demonstrated optical 3dB bandwidths that are in excess of 250GHz[7] as seen in Figure 5 and plasmonic ring

[5] Arista presentation from OFC 2023 for elimination of DSP using Linear Drive Optics (LDO)
[6] LWLG at https://www.lightwavelogic.com/presentation/8th-photonic-integrated-circuits-pic-international-conference/
[7] Polariton (post deadline paper ECOC 2022), LWLG

resonator slot modulators similarly with over 100GHz[8] as seen in Figure 6 and the table in Figure 7

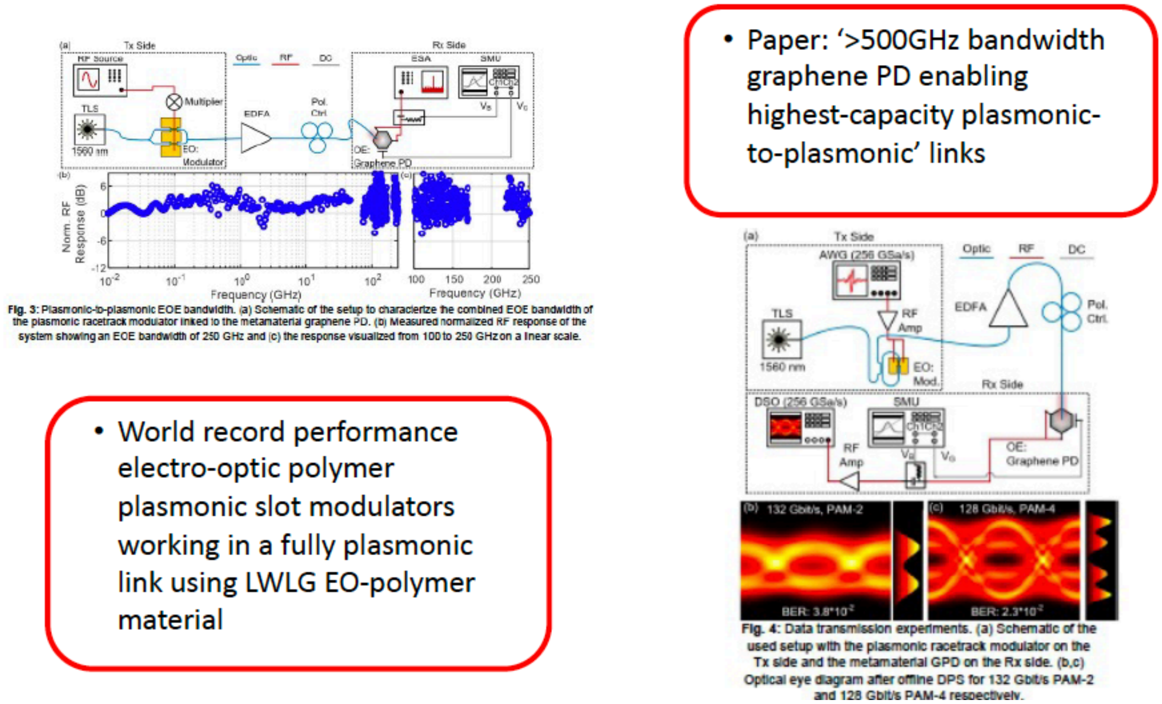

Figure 5: Active electro-optic polymers implemented into plasmonic slot modulators with >250GHz 3dB bandwidth (Sources: Polariton (plasmonic slot modulators), LWLG (polymer))

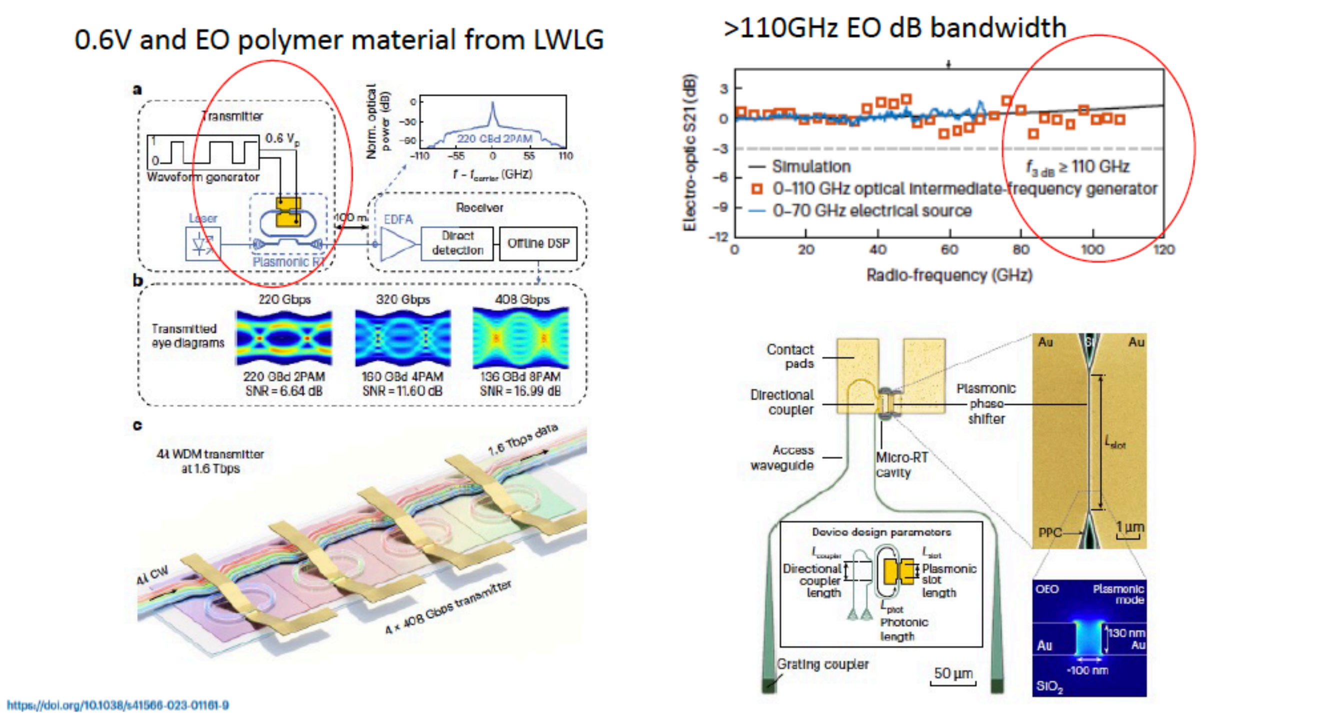

Figure 6: Active electro-optic polymers implemented into plasmonic ring resonator slot modulators with >110GHz 3dB bandwidth (Sources: ETH Zurich, Polariton, LWLG (active electro-optic polymer), https://doi.org.10.1038/s41566-023-01161-9)

[8] ETH Zurich, Polarition, LWLG, https://doi.org.10.1038/s41566-023-01161-9

- World record performance of electro-optic polymer plasmonic ring resonator modulators compared to competitive ring resonators in silicon & TFLN

Table 1 | Literature overview of geometric, resonance and data transmission properties of published resonant modulators achieving >60 Gbps

Type	Reference	Circumference (μm)	FSR (nm)	Q factor	$V_\pi L$ (V μm)	Electrical tuning (pm V^{-1})	Bandwidth (GHz)	Modulation format	Line rate (Gbps)	Driving voltage (V_p)
Plasmonic MRM	15	6	115	30	*	2,750	>115	2PAM	72	3.3
Si MRM	52	31	13	4,800	3,700	33	45	2PAM	60	0.8
								4PAM	100	1.25
Si MRM	53	31	20	3,000	*	33	55	4PAM	160	1.2
Si RT	54	60	7	5,600	8,000	26	79	2PAM	120	*
								4PAM	200	*
Si RT	24	60	7	5,600	8,000	26	67	DMT	301	*
Si MRM	55	38	11	4,200	5,300	*	77	2PAM	128	0.4
								4PAM	192	0.8
Si MRM	25	25	16	4,000	5,300	*	62	4PAM	240	0.9
TFLN Bragg	56	*	*	200,000	*	15	60	2PAM	100	0.9
								4PAM	100	0.9
Plasmonic RT	This work	~90	7	~700	150	>178	176	2PAM	220	0.6
								4PAM	320	0.6
								8PAM	408	0.6

The plasmonic RTs presented in this work achieve 1.7 times improved data transmission speed (for intensity-modulated/PAM formats) with low 0.6 V_p driving voltage and a 2.2 times increased bandwidth over Si MRMs. TFLN, thin-film lithium niobate. Values denoted with * are not available.

Figure 7: Table showing active electro-optic polymer plasmonic ring resonators with significantly higher performance in bandwidth compared to silicon ring resonators (Sources: ETH Zurich, Polariton, LWLG, https://doi.org.10.1038/s41566-023-01161-9)

This approximately translates to line rates that not only exceed 200G PAM4 which is where the datacomunications and datacenter industry is today in 2023 but offers line rate potential of 300G and even 400G in the near future. These line rates will enable pluggable optical transceivers to be designed with aggregate data rates of 800Gbps, 1600Gbps (or 1.6Tbps), 3200Gbps, 6400Gbps and beyond as can bee seen in Figure 8.

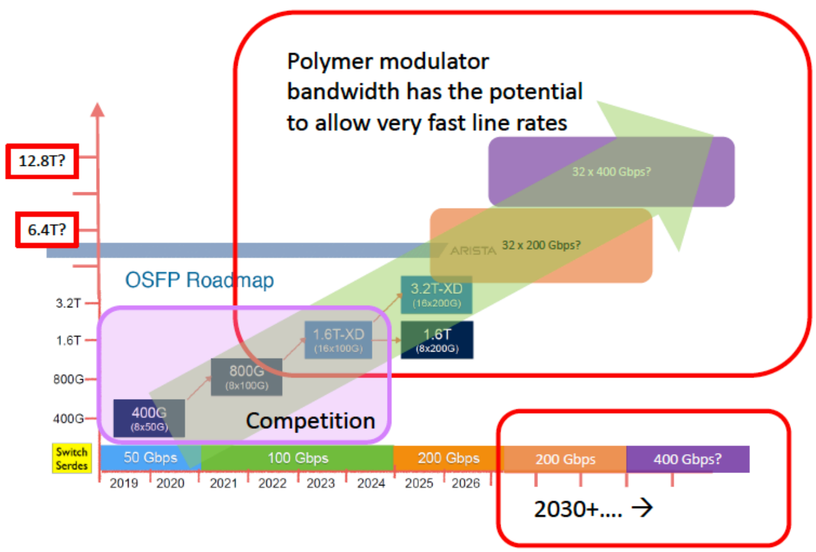

Figure 8: Graph showing a roadmap for OSFP optical pluggable transceivers with aggregate data rates and a timeline for switch serdies and the potential impact for active electro-optic polymer modulators. (Sources: LWLG, Arista, OSFP MSA)

INDUSTRY NEEDS:

Unlike conventional modulator materials, the polymer material system for both active and passive solutions have natural abilities that is attracting attention from the fiber optic communication industry. Several commercial companies are currently designing commercial high speed optical modulators made from electro-optic polymers that will be capable of 200G line rates using 3dB bandwidths more than 70GHz. Technical data showing 3dB bandwidths that exceed 250 GHz (corresponding to approximately 3-400G line rates) have already been demonstrated, which indicates even higher speeds should be possible in future.9 The polymer material system also has the potential of extremely low voltage levels that can reach below 1V. Furthermore, the polymer material system has the potential for small device size and in fact, small enough to fit into standard fiber optic transceiver form factors that are used for 100G today, and 200G communications that are emerging in the 2023 and 2024 timeframe.

The polymer material breaks through the technology barrier and opens up new possibilities. Two examples of solutions that could inhabit the new design space are shown in green below. It is expected that the industry roadmap will be extended to >100GHz bandwidth devices in the next few years, and >200GHz over the next decade.

Table 2. *Polymer needs for devices, reliability and hybrid integration*

Needs < 5 years

- Device speed increased (bandwidths EO S21 of 80-100GHz (polymer modulator) in PIC platform
- Drive voltage at 1V (polymer modulator) so that drivers can be eliminated
- Reliability data set for reliability of polymer modulators
- Hybrid integration onto silicon photonics PIC platforms

Needs 5-10 years

- Device speed increased (bandwidths EO S21 of 120-150GHz+ (polymer modulator) in PIC platform (for 200Gbps NRZ data rate or 600Gbaud PAM4)
- Drive voltage less than 1V (polymer modulator) so that drivers can be eliminated (direct drive from CMOS ICs)
- Reliability data set for reliability of polymer modulators
  Hybrid integration with semiconductor PIC platforms

Needs > 20 years

- Device speed increased (bandwidths EO S21 of 150-250GHz+ (polymer modulator) in PIC platform (for 300Gbps NRZ data rate or 500Gbaud PAM4)
- Drive voltage less than 1V (polymer modulator) so that drivers can be eliminated (direct drive from CMOS ICs)
- Reliability data set for reliability of polymer modulators
  Hybrid integration with semiconductor PIC platforms

[9] Source: M. Lebby. [Online]. https://www.lightwavelogic.com/presentation/2023-annual-shareholder-meeting-management-presentation/

CONTRIBUTORS

Michael Lebby, Lightwave Logic Inc. – chair (michael@lightwavelogic.com)

Polymer group members:

Nikolaus Floery, Vario-Optics (n.floery@vario-optics.ch)
Yuichi Nanakahara, Ajinomoto Co (yuichi.nakahara.s5k@asv.ajinomoto.com)
Brian Wilbur, Brewer Science (bwilbur@brewerscience.com
Nick Singh, Photon First (nick.singh@photonfirst.com)
Atikem Haile-Mariam, Lightwave Logic Inc. (atikem@lightwavelogic.com)

APPENDIX B-1

INTRODUCTION TO ACTIVE AND PASSIVE POLYMERS

Polymer (organic) based technologies for optoelectronic and photonic applications have been developed by both academia and industry over the past 40+ years and are currently in the process of commercialization with the first announcements of active polymers occurring in 2023.

Two types of active polymers have made significant progress over the past 2years and include silicon slot modulators and plasmonic slot modulators where the active electro-optic polymer is used to create an optical modulator device. Both modulator device varieties have demonstrated performance metrics that have far exceeded incumbent semiconductor commercial product today, and both platforms are expected to mature further and displace semiconductor optical modulators for fiber optics communication-based applications.

Both active and passive polymers have been researched, optimized, developed over the past few decades with passive polymers commercialized in the 1980s. In fact, going back to the 1970s, there was strong government funding as can be seen in the figure below for active (or electro-optic) and passive organic polymers globally. In USA, Federal Government agencies such as DARPA, NSF, DOE and DOD etc., provided a strong support system for academics to research polymer materials that would have applications both actively with electro-optic properties, as well as passively for waveguides and other passive functions. Interestingly, the technology journal publications and textbooks on active and passive polymers from the 1970s are detailed and show how polymers could significantly increase the performance of optoelectronic integration of electronics and photonics (although at the time the term photonics was limited to passive devices only, which is not the case today).

By the time the 1980s came around, large corporations in industry had joined the government funding agencies to increase the total funding of polymers for photonics with companies such as AT&T Bell Labs, Motorola, Du Pont, GE, Lockheed, Dow, Akzo Noble, Philips, IBM, Intel, Boeing joined in with well-funded industrial R&D laboratories.

While in the 1970s, 80s and 90s, there was significant research works for active organic polymers in the fiber communications space, it was the display application that managed to demonstrate high volume, commercial success with active polymers called organic LEDs (OLEDs). Organic LEDs use an organic polymer that similar to active or electro-optic polymers for fiber optic communications that are also biased with a voltage. The different chemical composition allows the polymers for organic LEDs to generate and emit light (typically red, green, and blue), however, in active electro-opitc polymers, light is modulated, switched, and not generated. The exciting observation on active electro-opitc polymers in general is that similar to OLEDs where the polymers out-perform LCDs on performance in contrast and speed, active polymers also outperform semiconductor modulators in speed, low power, as well as small size or footprint.

Given the success and learning that the OLED industry has seen over the past decade, it remaims to be seen if the companies and community who are working on active electro-optic polymers can follow the same commercial success path with modulator devices. Displacing an incumbent semiconductor modulator technology is not easy, but then who uses a LCD display these days? It’s all polymer-based OLEDs whether the display is in a mobile phone, personal display assistant, lap-top, monitor, or TV. The same change is predicted for active electro-optic polymers over the next decade.

APPENDIX B-1A

PASSIVE POLYMERS – WAVEGUIDE PLATFORMS

While passive polymers have seen limited levels of commercial success with optical board platforms, such as printed circuit boards, the rise of the interposer, co-packaging, and small form factor optical engine-based solutions will generate large opportutnities for passive polymers over and above optical polymer lenses, and polymer packaging that includes polymer optical coupling using complex polymer optical wires. Figure 5 below shows the standard designs and architectures for passive polymer waveguides. Passive polymers also include polymer optical fiber, polymer connectors and adapters, and laminates for high RF performance with both electronics and photonics. Commercialization of passive polymers for plastic optical fiber, polymer based pcb's, polymer waveguides, polymer waveguide interface vehicles (between pcb's, transceivers, modules to glass fiber optic cables), as well as various forms of polymer optical lenses is expected to continue and grow over the next decade to the point of displacing incumbent glass, semiconductor, and board-based technologies gradually.

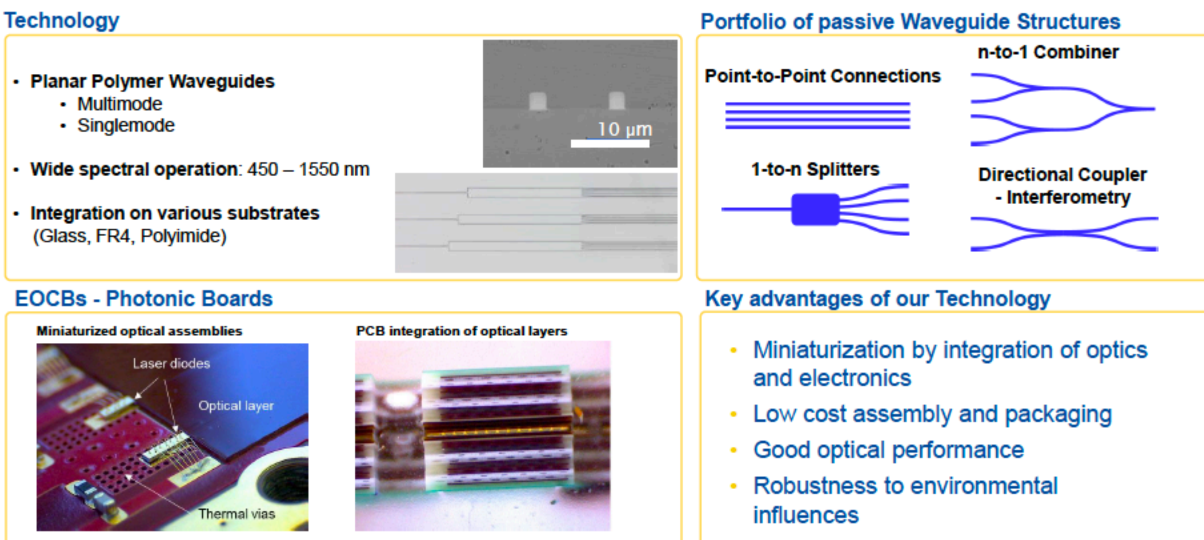

Figure 9 Passive polymer waveguide structures and advantages (Source: Vario-Optics)

Passive polymer waveguide technology can be arrayed easily to allow for multichannel interface untis, as well as advanced co-packaging solutions as photonics becomes geographically closer to electronics (with mid-board engines) for more efficient architectures in optical networking switches and routers. Polymer optical waveguides that demonstrated 1.4Tbps operation are shown in Figure 10 below, as well as sensors in Figure 11, and applications to silicon photonics and InP for data communications in Figure 12 below:

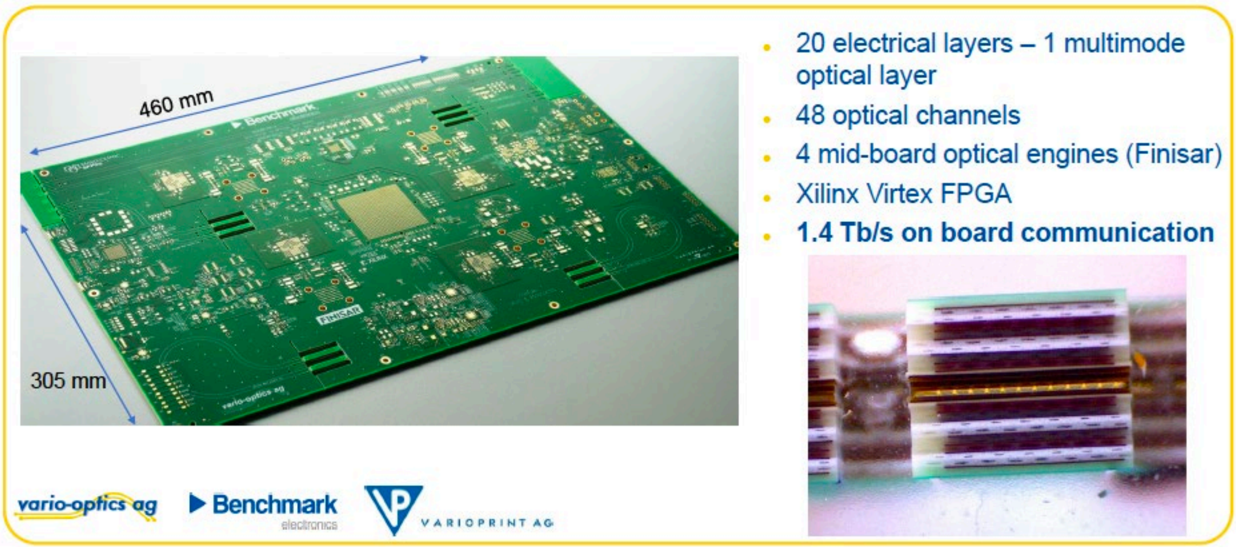

Figure 10 Passive polymer waveguide structures and advantages (Source: Vario-Optics, Benchmark, Varioprint AG)

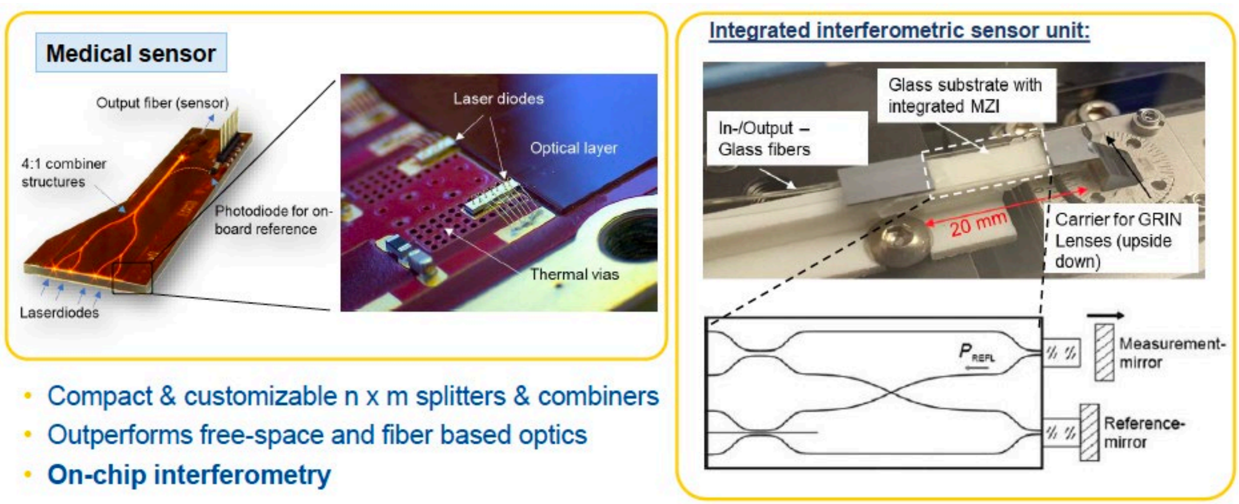

Figure 11 Passive polymers with applications of medical sensors using interferometric designs (Source: Vario-Optics)

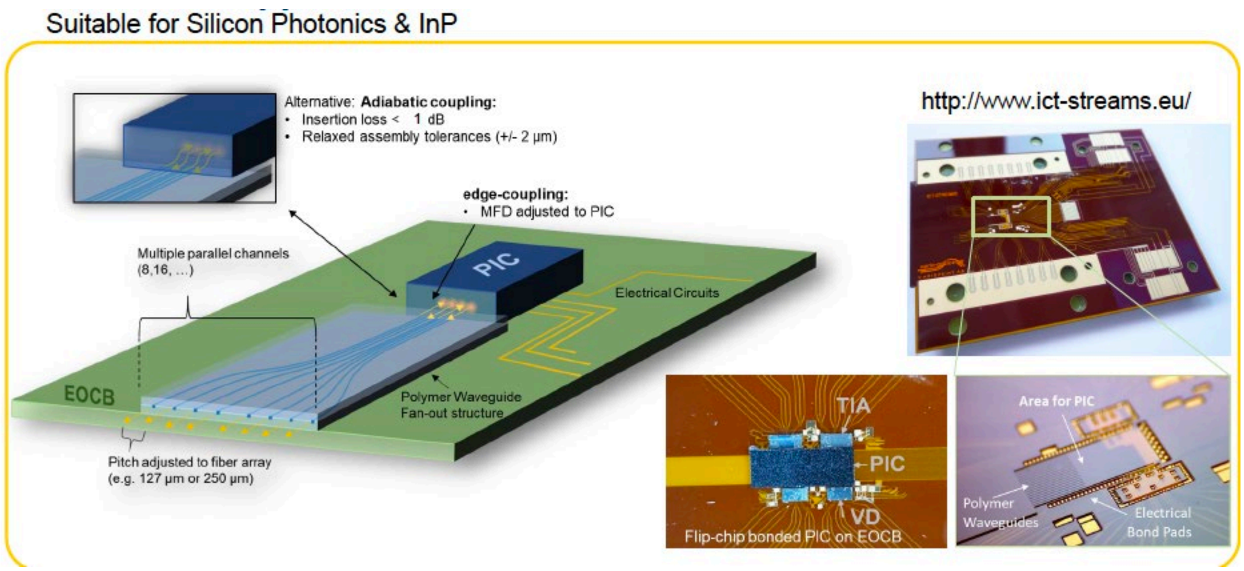

Figure 12 Passive polymers with applications for datacenters and PIC platforms such as silcon photonics and InP (Source: Vario-Optics)

APPENDIX B-1B

PLASTIC POLYMER FIBER (POF)

Plastic polymer fiber10 has experienced extensive research and development in the 1980s and 1990s, with many technological improvements in stability, robustness and lower attenuation. Further, from a commercial standpoint, POF has niche commercial markets in illumination (where heat generated was low), short distance optical interconnects for automotive applications and instruments. POF dimensions compared to silica glass fiber is shown in Figure 13.

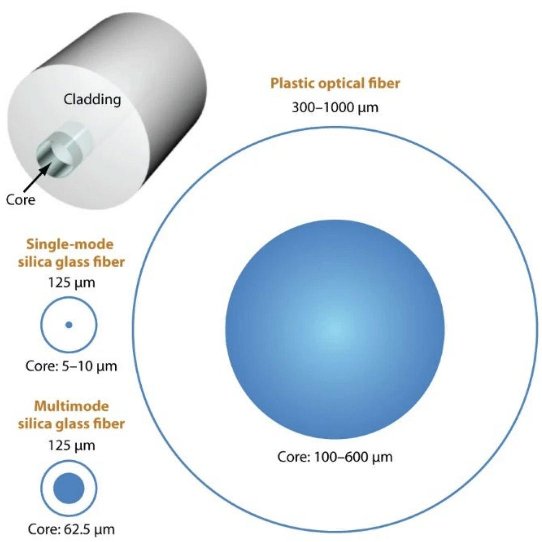

Figure 13 POF cross-section compared to silica glass fiber (Source: NPG Asia Materials (NPG Asia Mater) ISSN 1884-4057 (online) ISSN 1884-4049 (print))

[10] Polymer Optical Fibers, Edited by Christian-Alexander Brunge, Woodhead Publishing (2017)

Over the past decade, many of these applications have given way to LEDs as well as laser diodes. However, there have been new opportunities created in very short optical interconnects within datacenter type applications where link reaches are 10m or less. Much of this market has been and continues to have a high market share by copper-based interconnects, especially at link reaches up to 3m. Furthermore, in consumer electronics, video interconnect standards now allow data rates up to 10 and 18Gbps for ultra high-definition video displays that provide high levels of dynamic range. These rates are set to continue and allow for further commercial opportunities for polymer based POF optical interconnects, as display technology complexity increases to 4k, 5k and 8k systems. It is expected that POF based polymer systems may reach data rates of 50Gbps or even 100Gbps as the trend continues. In the automotive industry, and optical networking for automotive vehicles that are driven by numerous cameras, entertainment, LIDAR and other sensing systems, data rates are expected to be driven to at least 10Gbps over the next decade, and even up to 100Gbps.

POF polymer fibers have now improved their attention (dB/km) to be more competitive for shorter distance interconnects, and this is shown in Figure 14 below:

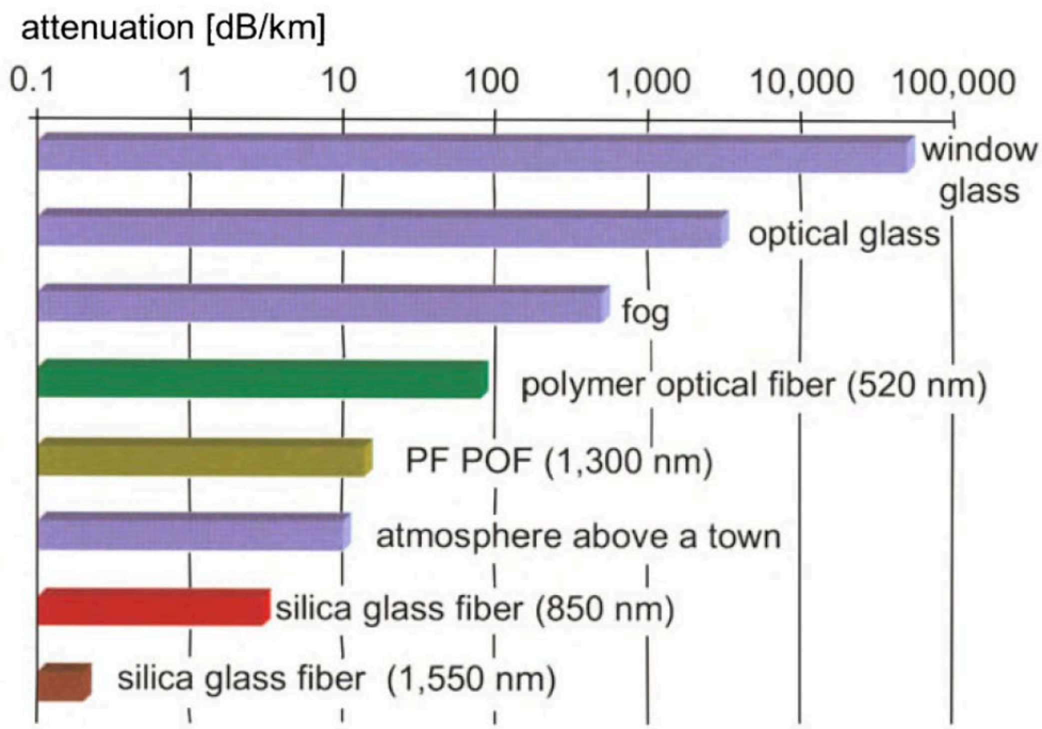

Figure 14: Comparison between different media (glass, polymer) that shows various level so attenuation.

POF has improved significantly over the last 2 decades[11], and is expected to continue increasing its commercial acceptance not only in the fiber optic communications industry, but also in other exciting consumer industries such as automotive, sensing, and entertainment.

[11] Fiber Optical Data Communication: Technological Trends and Advances, Edited by Casimer DeCusatis, Academic Press (2002).

APPENDIX B-2

SITUATIONAL ANALYSIS FOR POLYMER MATERIALS

Fiber optic communications is the lifeblood of our information economy. As the amount of data that the world relies on continues to grow inexorably, the speed of fiber connections has reached astounding rates. Back in the late 1990s, only the big data pipes of the “information superhighway” national infrastructure relied on fiber optics that ran at 1 or 2 gigabits per second. Today, the consumer at the edge of the network is being offered gigabit broadband service; tomorrow, the next big cellular upgrade to 5G promises “Multi-gigabit (per second) Internet” to your phone. Meanwhile, the big pipes that aggregate entire cities’ worth of traffic to send to the giant datacenters for processing have grown to 100’s of gigabits per second - and are still expected to grow significantly over the next decade. Fiber optics, in many forms, permeate the network from residential broadband to intra-datacenter to national and international backbones.

The challenge to increase optical device analog bandwidth is complex and while custom device designs have shown the potential for optical analog bandwidths that exceed 100GHz, generally these results are academic, and are far from commercialization. While the end of electronics’ Moore’s Law is widely discussed in the semiconductor community, leading fiber optic technologists are giving papers about approaching fundamental limits with optical devices that focus on quantum approaches. It does not mean that progress will stop, but it does mean continued progress will require more ingenuity (and complexity) than before. One major opportunity is the rapidly developing segment of fiber optics and the type that carry traffic in and between giant datacenters. In fact, it has been complex and difficult for the industry to get to where it is today and why a new direction is needed now. This opens the door to see how polymers could be key to continued access to more data. This would be commercially beneficial for the polymer community as passive polymer optical components such as lenses, optics, waveguides, spot size convertors and other related components have enjoyed relative success in the fiber optic communications segments of the datacom and telecommunications markets.

APPENDIX B-2A

TWO PHOTON POLYMERIZATION (TPP)

New areas of interest for polymers include Two-Photon Polymerization (TPP) which can include 3D lithography, and applications such as photonic wire bonding, freeform lenses etc.

APPENDIX B-2B

3D LITHOGRAPHY

This polymer process of TPP utilizes a maskless direct laser writing platform. For the TPP process in general, the light-matter interaction only takes place within the volume of a focused laser spot. In this situation, the simultaneous absorption of two photons in the focused spot area triggers the locally confined polymerization of an exposed photosensitive organic material.   The advantage of TPP is that the laser beam and focus point can be easily moved throughout the volume of the organic photoresist in 3D. This allows a wide degree of freedom in design (see sub-section on photonic wire bonds for example). It also allows with good modeling and simulation support the design and creation of complex 3D structures to be defined and physically written along the movement of the laser beam itself.

One of the first applications for TPP are micro-optics which can benefit hugely from freefrom designs and shapes to create optical mode profiles for higher performance coupling of light. Other applications include photonics in general, displays, sensors, micro-mechanics (i.e. micro gears, and motors), and medical as can be see from examples in Figure 15 and 16.

The main advantages of TTP include high resolution of organic polyme structures in a 3D environment. Further, complex organic structures can be fabricated just like conventional 3D printing technologies where multiple layers are deposited such as stereolithography.

The use of non-linear absorption for the TPP process that resolutions for polymer designs can be below the diffraction limit. Printing resolution at the 100 nm scale can be achieved easily using the technique. This allows for designs to accurate and of high quality (sub-micron scale) and the resolution is therefore not limited by diffraction, as opposed to conventional laser scanning methods.

TPP has excellent compatibility with semiconductor fabrication process techniques used in foundries as the materials are similar. Materials such as photoresists and solvents are used and these are standard in foundries today

For hybrid 3D TTP techniques and processes, polymer organic photonics structures can be printed directly on active photonic devices such as VCSELs, semiconductor lasers, photodetectors and fiber-based components such as fibers, lenses etc. TPP has the advantage to reduce assembly and alignment processes between individual compoments.

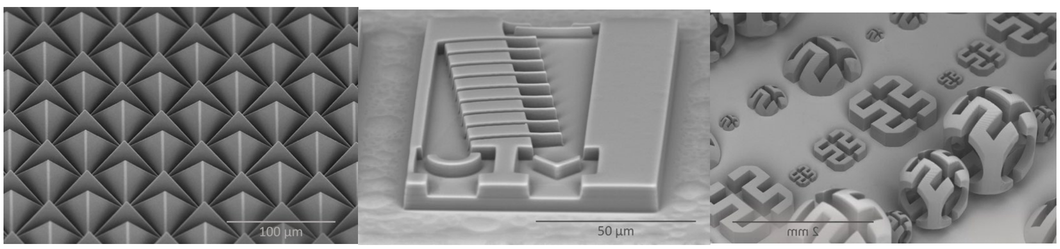

Figure 15: TTP in various applications and designs: a) Retro-reflector, b) Micro-fluid reactor, and c) 3D structures for life science (Source: Heidelberg Instruments)

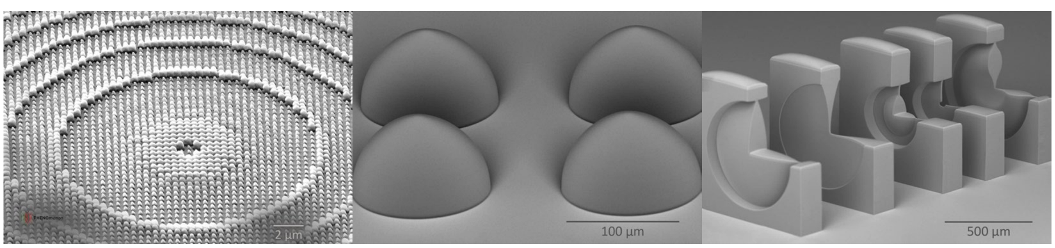

Figure 16: TPP in various applications and designs: a) Metalens for sub-diffraction limit, b) Micro-freeform lenses, and c) Vertical lens system (Source: Heidelberg Instruments)

APPENDIX B-2C

POLYMER WIRE BONDS

Two photon polymermization (TPP)[12] can we designed to create optical polymer wire bonds as can be seen in Figure 17 below where manufacturing techniques are utilized to create free-form optical wire bonds that connect several semiconductor chips optically. This technology has been developed by KIT university in Germany over the past half-decade and looks attractive in helping alleviate chip to chip optical communications over the next decade as can be seen in Figure 18.

[12] https://www.cell.com/iscience/pdf/S2589-0042(23)00451-0.pdf Two decades of two-photon lithography: Materials science perspective for additive manufacturing of 2D/3D nano-microstructures (April 2023)

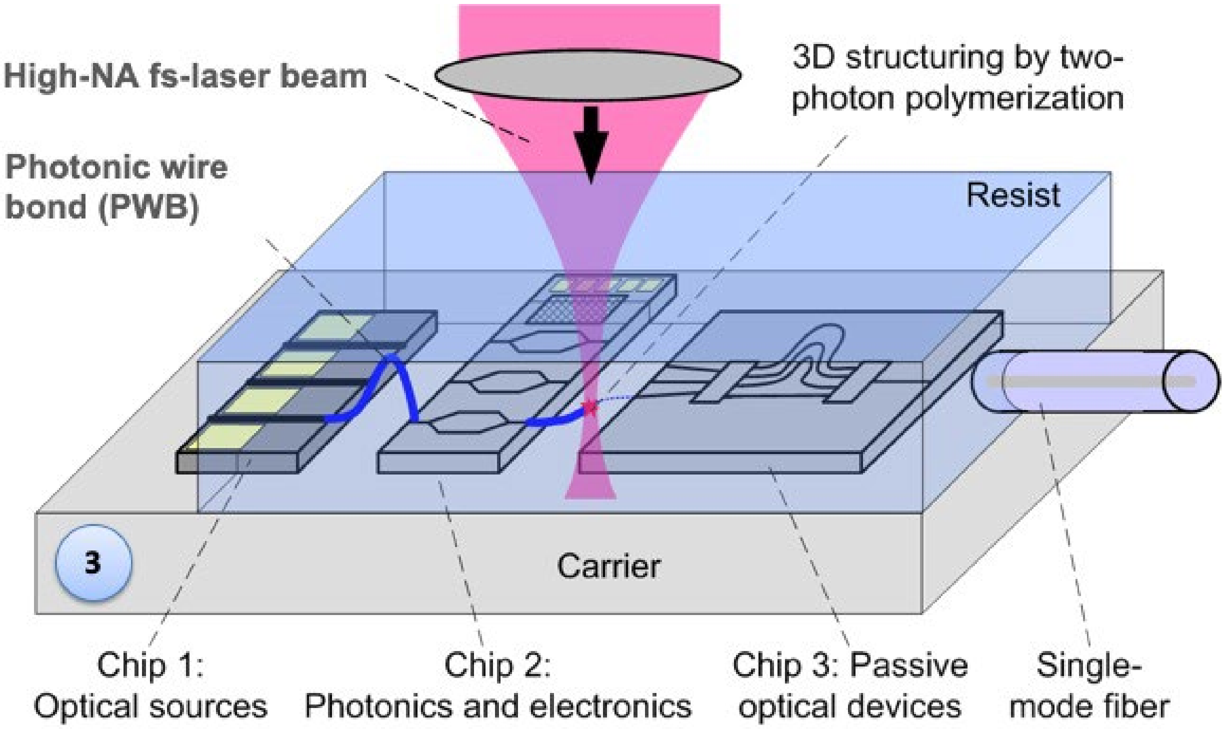

Figure 17: The shape of the photonic wire bond (PWB) waveguide is designed according to the recorded facet positions and defined using two-photon polymerization lithography.(Source: Vanguard Automation)

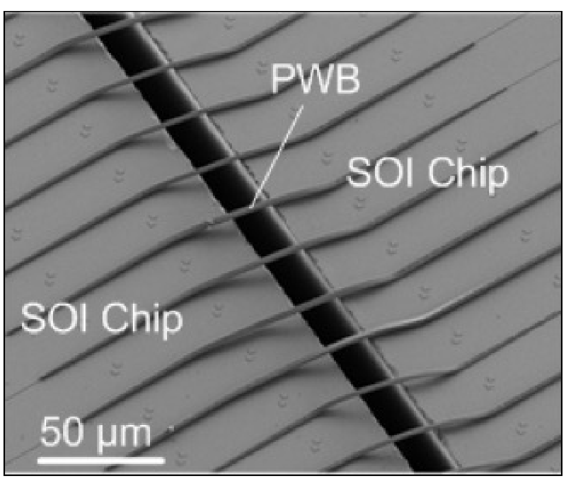

Figure 18 Polymer wirebonds shown with two silicon on insulator (SOI) chips connected via free-form photonic wire bonds to form a multi-chip-module (Source: Vanguard Automation)

APPENDIX B-2D

FREEFORM OPTICS

Freeform optics are freeform shapes that can have a non-constant, non-symmetrical curvature and little or no symmetry. In their present form they offer attractive uses over conventional polymer optics such as diffractive, refractive, spherical, aspherical surfaces and lens technology. The surfaces are different in that they advance traditional technological solutions into new and novel optical designs. Freeform optics is an emerging discipline that offers improved performance with larger field of view (FOV), better and more optimized illumination, miniaturization, less lens elements, lighter weight, improved micro-less arrays formats, and much improved design flexibility. The first major R&D developments in freeform optics were undertaken by by Polaroid in the early 1970s, and further advanced over the following decade. Freeform optics have the potential over the next decade to change the way optical systems are designed and utilized.

Recently in Europe, a European funded pilot line was inititated called Phabulous for the advanced manufacturing (at pilot line level) of optical free-form micro-structures.[13] Key players in the Phabulous pilot line are shown in Figure 19.

Figure 19: EU funded pilot line "Phabulous" that is focused on free-from optics (Source: Phabulou.eu,with members including: CSEM (Switzerland), Joanneum Research (Austria), Fraunhofer FEP (Germany), CEA-Leti (France), SUSS MicroOptics (Switzerland), Morphotonics (Netherlands), Nanocomp (Finland), Wielandt UPMT (Belgium), LASEA (Belgium), PowerPhotonic (United Kingdom),Limbak (Spain), EPIC (France), AMIRES (Czech Republic) and potential customers such as Hella, BMW, Swarovski)

Free-form micro-optics can generate new and exciting applications that include for example displays and luxury goods. In the area of displays, free-form micro-optics can be used for brightness enhancement of OLED micro-displays. The freeform microlens arrays can provide advantages for improving pixel luminance of OLED micro-displays, especially for Augmented Reality (AR) applications with see-through glasses. The main goal for this use application is to control the angular shape of light output and to enhance brightness of the OLED micro- display

[13] https://phabulous.eu/pilot-line/

components, especially in connection with compact, free-space optics based micro-projection systems for wearable Augmented Reality applications. In the areas for luxury goods, and structured patterns, free-form micro-optics can provide micro-structured foils and panels with gemstone appearance. Free-from surface micro-structuring can provide high brilliance for soils and panels expanding design freedom and opening the door to new designs. Further, the large areas roll-to-roll (R2R) and roll-to-plate (R2P) replication technologies offered by Phabulous pilot line have great potential for interior walls and large surface area structures.

Freeform microstructured foils/plates with gemstone appearance are a huge potential for the technology. Below is an image of a hexagon panel based on a honeycomb design that has sparkled on spectacular facades world-wide. In this example in Figure 20 below an active panel combines the luminous power of 200,000 crystals per square meter with a backlighting of custom LEDs and free-form optics.

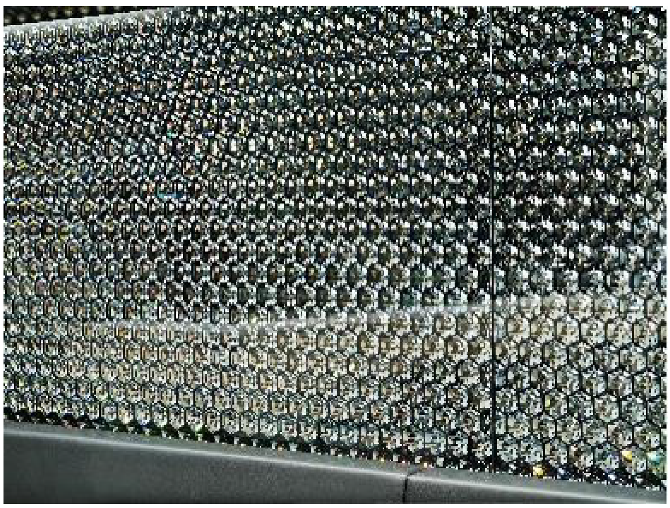

Figure 20: A hexagon panel using freeform microstructured foils/plates with a gemstone appearance.

APPENDIX B-2E

HYBRID FREEFORM OPTICS USING TPP

Micro lens applications of TPP with freeform optics can be created using hybrid photonic integration. This technique combines design advantages of different material platforms and potentially can perform better than monolithic approaches to optics. Key to micro-lens application can be attached facets that give the designer a higher level of flexibility with multiple chip scenarios that can be found in typical printed circuit board scenarios. One key advantage of using hybrid micro lens techniques is the ease of optical alignment between different discrete components, and the simiplification of high-volume assembly processes. Hybrid micro-lens techniques can model and simulate high performance optical mode profiles and then design optical lenses to achieve the simulated performance using TPP. In Figure 21 below is an image of in-situ printing of facet-atteched beam-shaping elements. These beam shaping elements have characteristics of dissimilar mode profiles and can have alignment tolerances that are compatible with high-volume passive assembly techniques. Some of the capabilities include beam-shaping elements at chip and fibre facets with optical coupling efficiencies of up to 88% between edge-emitting lasers and single-mode fibres. Other capabilities include the printing of free-form mirrors that simultaneously adapt beam shape and propagation direction.

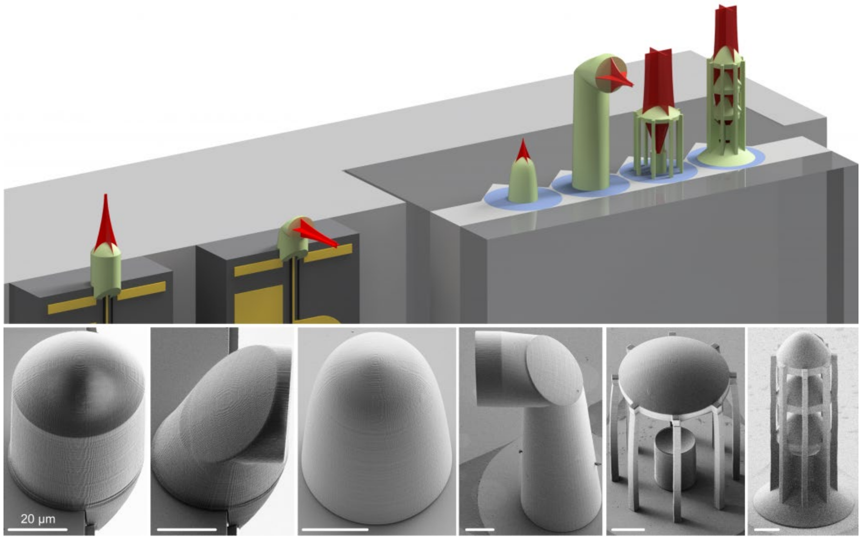

Figure 21: Freeform optics using facet attached micro lens designs (Source: Vanguard Automation)

APPENDIX B-3

POLYMER TECHNOLOGY

Polymer material offers huge opportunities to push the boundaries of the performance in optical devices such as modulators, optical lensing, optical packaging, optical pcb design, and optical connectors. Polymers are typically categorized into 2 areas: *active* and *passive*. Active polymers include an electro-optic effect and have been researched and developed for a number of applications over and above fiber optic communications. Passive polymers have been developed predominantly as an optical waveguide technology.

Polymers are *additive* to other competitive technology platforms as can be seen in Figure 22. As polymers can be spun on as planar layers in a fabrication plant, polymers can be added to InP, GaAs, and silicon photonics technology platforms. For example, an InP laser can be integrated with a polymer modulator, while a GaAs VCSEL which is utilized in 3D sensing could also be integrated with polymer functions that could include a modulator, multiplexor, or waveguides.

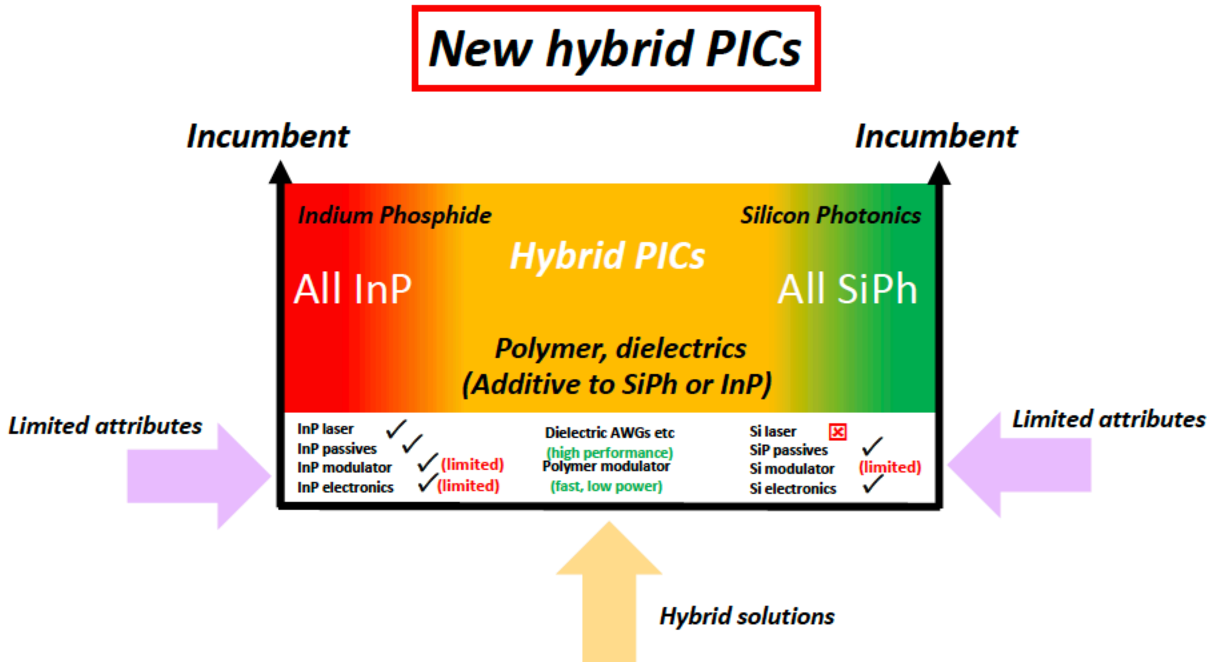

Figure 22: Active electro-optic polymers as an additive platform to Indium Phosphide (InP) and or Silicon Photonics (SiP) (Source: LWLG)

One of the key areas that will require strong focus within the polymers segment is reliability. Like OLEDs when the technology was maturing in the early 2000s, a reliability data set is needed to convince end users that there is stability and reliability in the polymer platform both at the materials level, as well as at the device and package level. For example, reliability testing of materials requires key metrics such as refractive index, photostability, Teng-Man (r_{33} electro-optic coefficient) testing[14], poling of polymer materials, temperature stability measurements; etc. The trend for polymers to be utilized on a silicon photonics platform has huge potential from a roadmap standpoint as polymers have the potential to drive performance beyond the purple brick wall more efficiently than other technologies on the roadmap.

Foundry compatibility for active electro-optic polymers will be instrumental for volume scaling with optical devices such as optical modulators as can bee seen from Figure 23. Active electro-optic polymers are compatible with standard silicon fabrication processing and tooling, and offer competitive advantage compared to other technologies that are being considered for optical modulators in the fiber communications segment.

[14] https://www.lightwavelogic.com/presentation/polymer-modulators-with-50ghz-performance-for-power-consumption-reduction-at-400-800-and-1600-gbaud-aggregated-datarates/

New technology	Foundry compatibility	Performance head room
Polymer (modulators)	Silicon, III-V	>100GHz many generations
Polymer plasmonic (modulators)	Silicon, III-V	>250GHz many generations
Polymer plasmonic rings (modulators)	Silicon, IIII-V	>250GHz many generations
Barium Titanate (modulators)	Silicon (?)	~70GHz (?)
Indium Phosphide (EAMs)	InP, Silicon with bonding	~ <70GHz
Silicon modulators	Silicon	~ <30-40GHz (doping)
Silicon Rings (modulators)	Silicon	~ <50-60GHz (thermal)
Thin Film Lithium Niobate (modulators)	Lithium Niobate Silicon ?	~ <70GHz (this generation)

Figure 23: Foundry compatibility for active electro-optic polymer modulators as a PIC platform compared to other technologies platforms (Source: LWLG)

APPENDIX B-3A

POLYMER OPTICAL MODULATORS

In the field of active electro-optic polymers, there has been significant technological and commercial progress.

This review looks at the effects of increasing computational processing from the rise and popularity of AI has on the internet or optical network. AI is driving higher computational processing which in turn is generating more traffic and lots of heat. Higher traffic, and power consumption are becoming a problem for the internet architectural infrastructure in places such as datacenters and need to be addressed quickly before they become a weakness or vulnerability, even the Achilles Heel for the industry…

A new polymer material for an optical component called a modulator is being developed to replace existing semiconductor modulators used today in the internet. A modulator in general switches and modulates light, and there are millions of these devices on the internet today. The current semiconductor incumbent solutions are struggling to deal with higher data-rates, higher traffic volumes and low power requirements that are necessary to cope with AI.

Polymer modulators are devices that are positioned in front lasers, that generate the light for the internet, and more specifically the fiber optic network that comprises the internet. These devices have a voltage applied to them to align the polymers so that ultra-fast modulation, at ultra-low power is enabled using electro-optic polymers. Active elecro-optic polymer materials, and the integrated photonic silicon circuits that are applied them to are reliable and stable in performance, similar in a simple way to OLEDs (Organic LEDs, which are polymers with a different chemical composition, but have the capability to emit light (red, green, blue), and differ from active electro-optic polymers which modulate and switch light very quickly, in fact much faster than incumbent semiconductor technologies being used today.

Polymer modulator devices have superior fast performance and lower power than existing technologies. The polymer modulator devices are fast, stable, reliable, have low power consumption and are very small in size. These are the metrics that the internet and optical networking folks are looking for with the technology.

A polymer modulator physically is a silicon-based chip roughly a few millimeters on each side and on the chip are areas where the polymer (chromophore) is deposited[15]. As can been seen from Figure 24, on one side of the chip, as input there is an optical signal in, an electrical signal in with data. You mix the two together on the chip, and you get a signal out that's optical that provides the information. It's a chip that actually provides the optical information that is sent down the fibers in the optical network, and can be routed using datacenters. These chips go essentially into large metallic racks that are typically 6-8 feet high and about 2 feet wide, and 2 feet deep. There are hundreds of these inside datacenters today. Each one of these racks make up the datacenter system and can include routers, switches, and memory units.

- **A modulator combines a Photonic Integrated Circuit (PIC) with radio-frequency (RF) electronics and an Electro-Optic Polymer (EOP)**
- **When voltage is applied to the modulator, the intensity of the optical output changes, converting electrical data (1's and 0's) into optical data**
- **There can be millions of modulators in a single data center**
- ***EO Polymer slot* modulators allow *for faster data rates, smaller sizes,* and *lower power…***

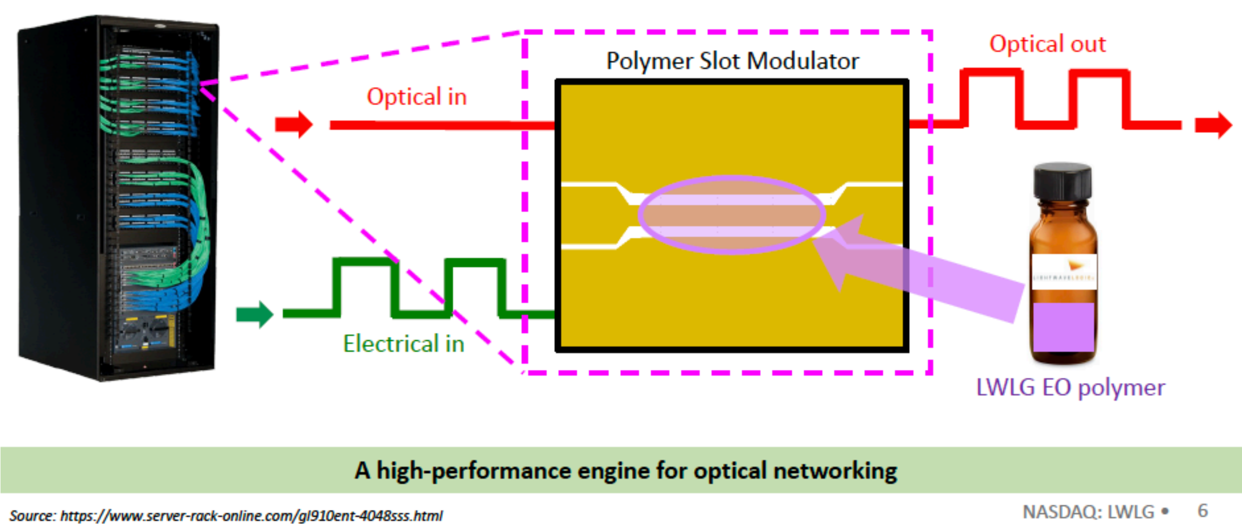

Figure 24: A polymer slot modulator is a component for datacenter equipment, (Source: LWLG, www.server-rack-online.com)

Polymer modulator technology can be viewed as a high-performance optical engine for optical networking. A modulator is part of a photonic integrated circuit (otherwise known as a PIC by engineers in the photonics industry). This is a chip with lots of different photonic devices, with radio frequency RF electronics, so it works at very high speed, and in the case with polymers it is a hybrid PIC using electro-optic polymers.

Overall, one way to look at electro-optic polymer technology is that it is solving a huge problem for the internet and optical networking, not just for today's generation of products, but for a long time, perhaps over a decade. Electro-optic polymers have inherent natural high performance, which allows them to have the potential to

[15] See Appendix footnote (6) of a graph that shows a polymer optical modulator how it is utilized. Source Lightwave Logic Inc.

extend out to several generations over the next decade. While there are other competitive technologies that are both incumbent as well as competing for new business, they unfortunately are only good for one generation. With polymers,' mother nature works with us', and 'not against us'. The natural technology high performance allows light to be modulated very quickly, at low power, and with tiny devices. Modulating light is an old concept, and a very simple way to look at this is liquid crystal displays (LCDs). Remember we all used LCDs in mobile phones, PDAs, monitors, and TVs over the years. LCDs modulate light also, but are very, very slow. Polymers are a faster technology, and the right application for this technology is the fiber optic network or Internet.

Polymer-based materials have similarities to OLEDs. It is amazing to think that 10 years ago we all had LCD displays, but now we have OLED displays. We all use polymers today with OLEDs: OLEDs stands for organic LEDs. The good news is that we don't even think twice about using polymers today when we view our color displays. With the success of OLEDs in displays, then there is a logical argument to suggest that a similar route can be taken for electro-optic (EO) polymers to become just as ubiquitous as OLEDs.

Polymer modulators are very small, which is a great benefit to put them inside boxes that go into these servers and routers in a datacenter, and these boxes are called pluggable transceivers. Being able to integrate polymer-based devices with other devices onto silicon photonics allows multi-functionality as well as parallel channels to increase the overall data-stream and information. That's important because these pluggable transceiver boxes are small in size (approximately 3-4 inches long by 1 inch wide). To shoehorn lots of different components in a small box means you must integrate them. Now we as an industry did this as an industry back in the 1960s with transistor based integrated circuits (ICs). Today we put a lot of transistors on a single chip because we benefit from small size, smaller power, and higher functionality – and in fact higher processing capability. The same sort of effect is happening in our industry in photonics albeit at lower levels of integration.

APPENDIX B-3B

POLYMER PERSPECTIVE

The takeaway so far is that active electro-optic polymer technology extends speeds, reduces power consumption, and not just for this generation of technology, for several generations. Even as far back as 2017, companies had unique chemistry for active electro-optic polymers and few in the community believed in active electro-optic polymers. The industry in general thought that polymer-based modulators had some potential, however, the industry really wasn't that interested. If we fast forward to today in 2023, the chemistry is still unique, and commercial companies have improved the performance of the materials significantly over the last five to six years to the point that today many in the industry not only believe in active polymers but are anxiously waiting for them.

APPENDIX B-3C

GROWING MARKETS FOR ACTIVE POLYMERS ENABLED BY ARTIFICAL INTELLIGENCE

There are three macro market areas that are driving the need for high performance photonic components that include polymer modulators and integrated photonics PICs chips, and these are: Switch density, artificial intelligence, and the need for green, low power. The first macro area of increased switch density has already become a big issue for datacenters with a need for space; the second area of artificial intelligence for increased computational processing has become a topical subject over the last few months with a need for speed, and lastly, the need for low power consumption, lower heat generation, and in general, the need for green and for lower power.

The end users need to seek an optical balance to make sure these macro drivers will drive the next-generation system and subassemblies using these components. Electro-optic polymer modulators have the potential as a key component to be a key enabler for the end users to achieve these types of criteria. This is exciting because is that these components can address the problems that these large companies are having and really address green, low power consumption, density, and high-speed communication of information.

As technologies become popular a good metric is to look to see how long it takes a technology platform to generate 1 million users. For example, in one interesting example[16], as seen in Figure 25 below, Netflix took ~3.5 years to reach a million users. Conversely, it took the more recent technology platform called ChatGPT only five days to reach a million users. The platform just got caught on like wildfire. ChatGPT is a platform like Bing, Bard etc., that allows users to experiment with artificial intelligence commands for simple projects. The observation from this technical perspective when something like this taking off in less than a week, means it has already had impact on society and is set to accelerate that impact very quickly indeed.

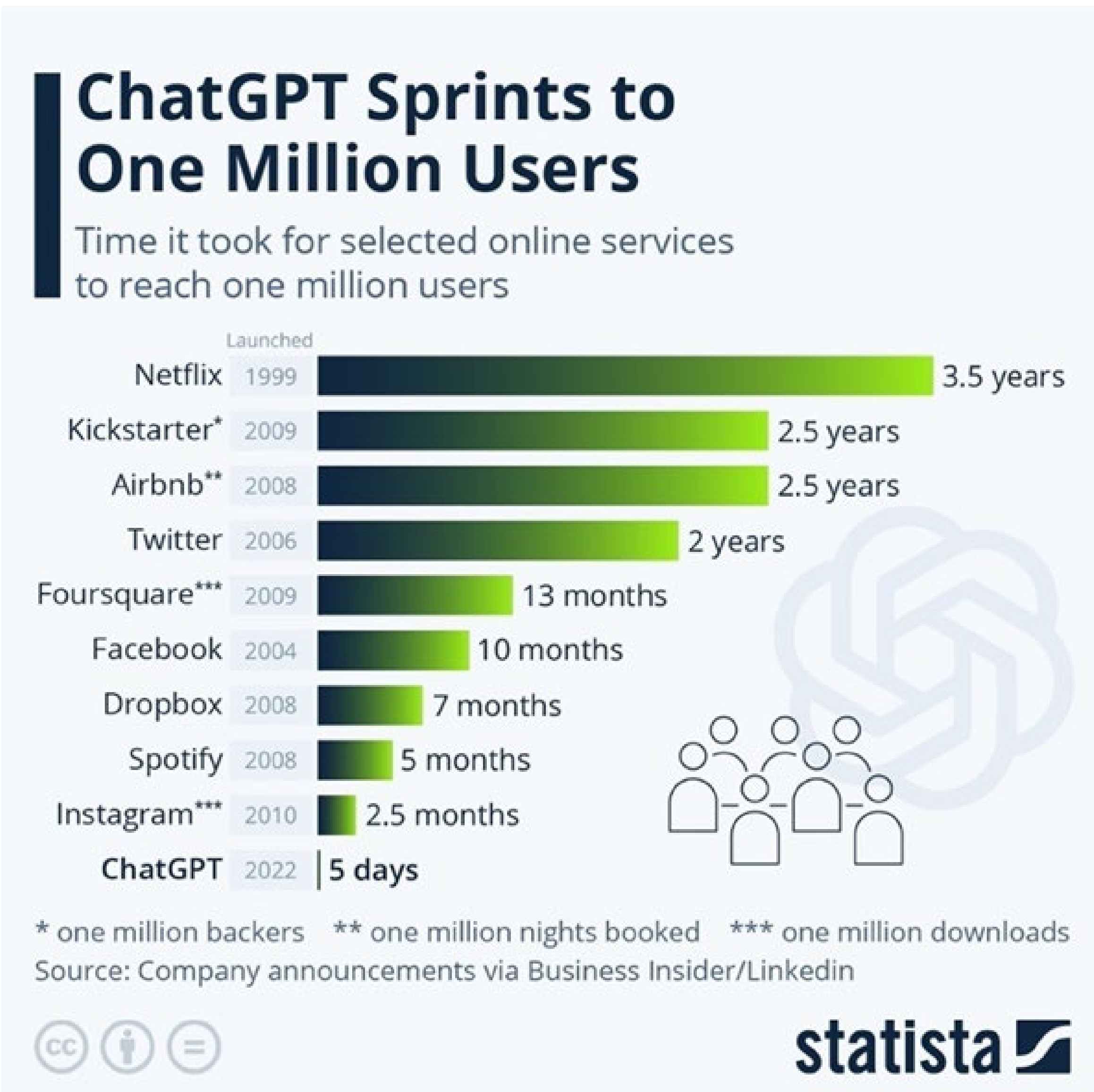

Figure 25: The time it took for selected online services to reach 1 million users, (Source: Statista.)

[16] Statista data graph.

APPENDIX B-3D

COMPUTING GROWTH

If we look at the growth of computing (or electronic processing) power in high computational processing systems over the past 60 years[17] from Figure 26 below we know that this growth has initially increased or doubled every 3-5years. Then from about 2020 onwards, the growth has increased by over an order of magnitude, or 10X, to a doubling of computational power every 3-4 months (in terms of petaflops - which is a metric for computational processing magnitude). This increase in computational processing has been driven at least for the most part by neural networks that compose artificial intelligence. This growth places significant strain on the infrastructure supporting computational processing. Key components for computing processing such as: Graphic processing units (GPUs) and Microprocessor units (MPUs) need to be upgraded; the capacity for optical signal information traveling down fibers needs to be increased; and the places where the electronic processing takes place, typically datacenters needed to deal with higher amounts of information. The economic cost for the internet and optical network operators will be expensive.

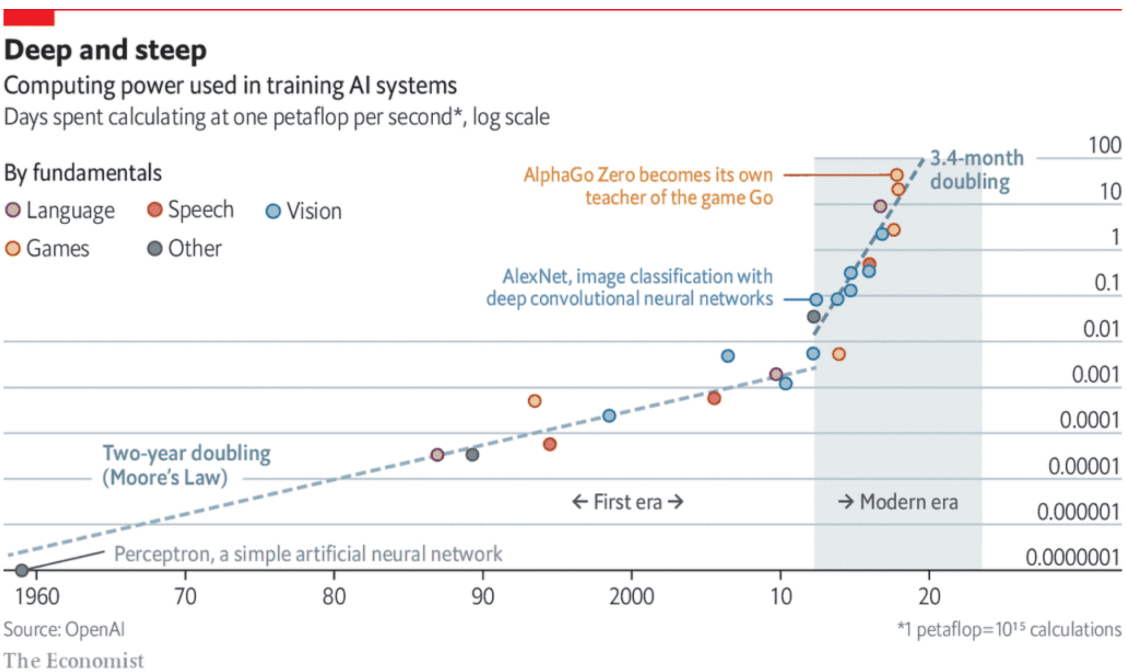

Figure 26: Computing power used in training AI systems (Source: Economist, and adapted from OpenAI)

APPENDIX B-3E

INTERNET AND OPTICAL NETWORK STRAIN

One way to think about the strain on the network is a simple analogy: Consider for a moment that the Internet is represented as the U.S. highway system, and you've got lots of freeways with several lanes, the computational processing for AI is basically the intersections between freeways. The impact of AI is telling us is that the intersections need to have three, four, five, six lanes because if you're in LA or in New York, it is the intersections that clog up first, because they need to get the traffic to the right destination. With the computing power doubling every two to four months it means that the datacenters that switch and route the traffic to destination

[17] Economist data graph with sources from OpenAI data.

are essentially clogging up. In means the folks who run and operate the datacenters need to update and upgrade them more quickly now. Upgrading a datacenter is known as a fork-lift upgrade, presumably as fork-lifts are used to exchange the heavy routers, switches etc., that are rack based. These fork-lift upgrades depending on each particular datacenter architecture tend to be every two to four years, but with AI and the surge of computational processing demands, this is quickly becoming a strain. It is expected to become a major headache for datacenter system architects. Further, the increased computing demands is driving power consumption up as well as increased traffic for the optical network or internet[18] as can be seen from Figure 27 below. This is because the increased computational processing from the use of AI in datacenters is generating more traffic for the internet.

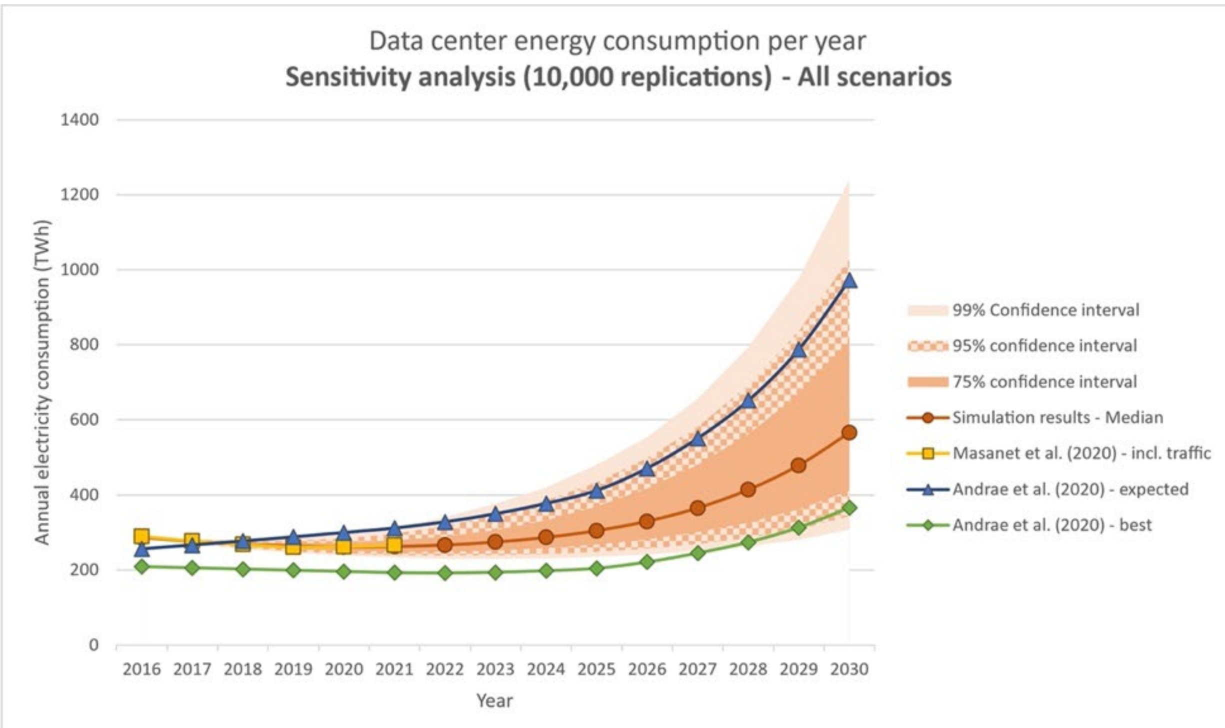

Figure 27: Data center energy consumption per year (Source: Applied Energy Vol., 291, 1 June 2021, 116798)

All these strains can be measured by two factors: power consumption and increased traffic. As the power consumption increases then more heat generated, which is something that datacenters would like to suppress with more efficient components. There are several graphs that show that the power generated in datacenters is rising exponentially, with no end in sight[19] as can be seen from Figure 28 below. The power consumption is on a trajectory that is not sustainable. The traffic, which is the data that gets sent down the Internet as information, that is now being generated in part by AI, is also on a trajectory that is not sustainable, and like power consumption, does not have a sustainable plateau in sight. These two big issues are worrying metrics for the datacenter community and have been called by industry experts as the industry 'Achilles Heel' as can be seen from Figure 28.

[18] Datacenter electricity needs from Applied Energy Vol., 291, 1 June 2021, 116798
[19] Datacenter electricity usage as well as increasing traffic adapted from Walnum, HJ et al and LWLG

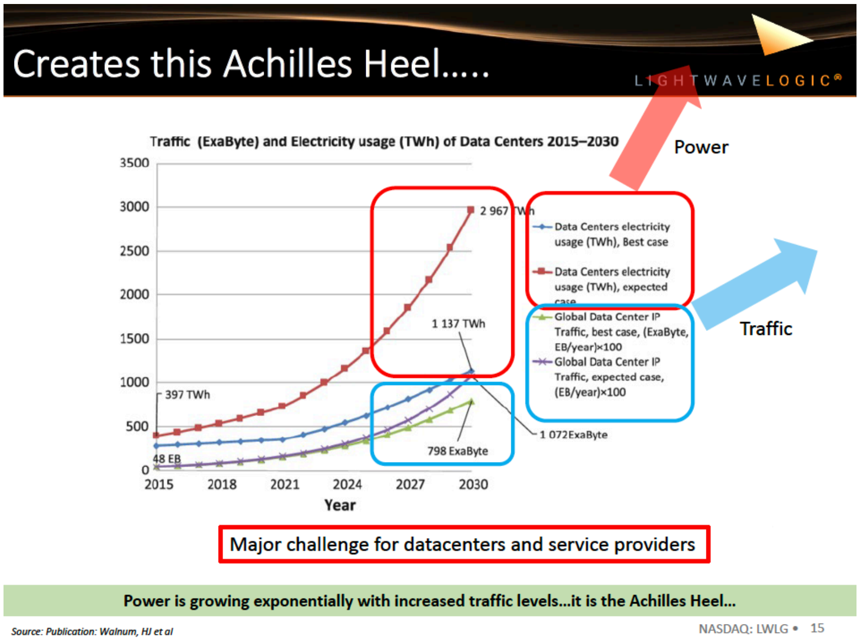

Figure 28: Traffic and electricity usage of data centers 2015-2030 (Source: Walnum, HJ et al, LWLG)

If we remember 20 years ago, we had dial-up modems which on average took 10-20mins to download one image, one photograph of our family. Then with technology advancements over the decade and about 10 years ago, it took us on average about 10-20mins to download a short video clip or TV show. If we look at the past decade, we know that the video was consuming a lot of traffic, and it still is, however, in the last year, video is being supplanted by artificial intelligence, or raw computational power. As we look forward to the next few years, even decade, this trend is set to grow at phenomenal rates.

APPENDIX B-3F

POLYMER MODULATORS ARE A STRONG SOLUTION FOR THE NEXT DECADE.

Polymer modulator technology is expected to address industry's roadblocks: High speed, low power, and tiny sized electro-optic polymer modulators that are designed into optical engines that go into optical pluggable transceiver boxes, which plug into datacenter switches, routers, and processing units. Polymer optical modulators are fast, small, and low power and are ideally suited to assist datacenters increase speed and keep power consumption in check.

Polymer optical modulators are a component that can indirectly assist AI. Polymer optical modulators do not affect the processing computational power of microprocessors or GPUs, because they're all electronics and are all transistors. It is these electronic chips that will generate more computations, more processing commands, and this ends up as more information. Information is then sent as traffic to other destinations. The more traffic means that the data that goes through the fiber optics is going to fill up more. Using the freeway analogy, this means that instead of having six freeway lanes full, there will be 10 freeway lanes full. In the end, AI is indirectly driving the deployment of more polymer optical modulators, and this will benefit companies designing optical components. Optical components such as polymer optical modulators are positioned in front of the laser that sends the light down the fiber optic cable. Higher traffic means more lasers, more modulators, and perhaps even more fibers that make up the internet infrastructure.

As is commonly known, there are many positives and negatives about AI today and even governments around the world are trying to understand the implications, however, the interesting observation is that internet users are experimenting on an individual level to learn how to use AI. This means we have millions and millions of innovators who will generate millions of new uses, new applications, and new effects for AI. Clearly, some of the effects of AI on society are unknown, and together with the increased investment by the datacenter companies, the field is expected to explode in activity soon.

APPENDIX B-3G

PASSIVE PLANAR POLYMER WAVEGUIDES

Planar polymer waveguide technology has been researched and developed since the 1980s with a number of publications and books at that time[20]. Over the last decade there have been an increased focus to implement passive planar polymer waveguides into fiber optics as well as a wide set of product applications. These applications have been driven from electro-optical circuit boards for ICT-application over electro-optical substrates for photonic packaging to sensor and Internet of Things (IoT) emerging applications. The optical material requirements for passive planar polymer waveguides is shown in Table 1.

Table 1. Passive planar polymer waveguide roadmap properties.

Item	Unit	Today	5 years	5-10 years	20years
Structuring		UV	UV	UV	UV
Refractive index		1.5	1.5-1.6	1.4-1.6	1.4. – 1.6
Numerical Aperture		0.1-0.3	0.1-0.4	0.1 -0.5	0.1 – 0.6
Optical loss @ vis	dB/cm	0.05 - 1	0.05 – 0.5	0.01 – 0.05	0.01 – 0.02
Optical loss @ 850nm	dB/cm	0.05	0.04	0.03	0.01
Optical loss @1310	dB/cm	0.5	0.2	0.1	0.05
Spectral bandwidth at 1310 nm	nm	80	120	160	200
Resistance against humidity / temperature		2000h @ 85°C / 85% rel h.	2000h @ 85°C / 85% rel h.	2000h @ 85°C / 85% rel h.	2000h @ 85°C / 85% rel h.
Short term temperature range	°C	-20 - +200	-20 - +200	-20 - +250	-20 - +300
Long-term temperature range	°C	-20 - +80	-40 - + 130	-40 - + 130	-40 - + 130
Compatible with PCB manufacturing processes		Yes	Yes	Yes	Yes
Step Index (MM)		Available	Available	Available	Available
Graded Index (MM)		Available	Available	Available	Available

[20] POF – Polymer Optical Fiber For Data Communication Applications, Daum, W, et al., Springer (2002).

APPENDIX B-3H

PASSIVE POLYMER STRUCTURES - OPTICAL FUNCTIONS

Multimode passive polymer structures.

Many passive polymer structures utilize multimode operation. With multimode designed structures, the optical alignment between waveguide and fiber is more relaxed (5-10 µm as opposed to 1-3 µm in single mode structures). This allows for faster and easier alignments, especially with automated alignment and pick and place tooling. Much of the multimode polymer technology, in particular planar polymer waveguides, is planar based. Common passive polymer structures include tapers, NxM splitters, NxM combiners, planar lenses etc.

Over the past decade, multimode passive polymer structures have matured successfully. There have been a number of commercial implementations into the fiber optic communications industry. The fortunate part of the technological fabrication and design process is in part due to the fact that photolithography can be executed on any optical structure so long as it is planar. With passive polymers for optical coupling there are a number of popular techniques today and include: butt coupling, vertical coupling via a mirror or a reflective surface, and connectors. All of these techniques are mature and over the next decade the improvements would be in the reduction of optical loss at each coupling mechanism. Again, compared to single mode, multimode waveguides have significantly larger dimensions. Multimode systems are therefore more tolerant towards mechanical displacement.

APPENDIX B-3I

SINGLE MODE PASSIVE POLYMER STRUCTURES.

In the single mode domain, there are a number of important optical "functions". One of the best examples is the appropriately designed directional coupler, which allows to interpose light waves in such a way that addition or subtraction can be realized. Optical alignment is tighter as the optical mode in the single mode structure is smaller (2-6 µm typically), however, the important optical functions include directional couplers, Mach Zehnder Interferometers (used as modulators), thermo-optical switching, and multipliers such as AWGs (arrayed waveguide gratings), vertical gratings, and Echelle gratings.

Also, for single mode, most of the relevant optical functions can be realized reasonably simply using polymers. The arrayed waveguide grating is more of a challenge for polymers, however over the next decade this structure should be available commercially. With single mode coupling, the same challenges exist over the next decade and that is a trend to reduce the optical loss in connection mechanism. Popular coupling mechanisms include butt coupling, connectors, evanescent coupling, vertical coupling, and grating couplers.

There will be improvements in the optical performance of vertical and grating couplers over the next decade as these mechanisms have the opportunity to reduce optical loss significantly. Vertical coupling to integrated planar polymer waveguides based on passively assembled devices is currently not available since the mechanical tolerances are very tight. Active assembly is currently very costly but with the expected improvements in mechatronics also this hurdle will be overcome over the next decade. Grating couplers based on integrated, planar polymer waveguides are not yet available commercially, however, this is expected to change quickly over the next decade.

APPENDIX B-3J

POLYMER SUBSTRATES

The roots of planar polymer waveguide technology are within the PCB industry, but it finds more and more applications within photonic packages. Today, planar polymer waveguides can be attached already to a large number of different substrates. The variety of substrates will further increase with the increasing number of applications based on planar polymer waveguide technology. In general, the substrates will base on similar material sets used within PCB industry, but also further materials will be used. Therefore, the list of substrates is not static and is subject to new developments.

Table 2. Passive planar polymer waveguide roadmap substrate properties

Substrate Materials	Today	5 years	5-10 years	20years
Glass reinforced PCB laminate	available	available	available	available
Polyimide	available	available	available	available
Glass / thin glass	available	available	available	available
Silicon	available	available	available	available
Teflon based substrates		available	available	available

The supported formats range from standard panel formats to smaller formats used for chip assembly. The maximum panel size is currently limited by the working space of actual photolithographic systems. But the mechatronic technologies are already available to support the large formats. The minimum die size is mainly limited by the handling systems for small devices.

Table 3. Passive planar polymer waveguide roadmap dimensional properties

Supported panel formats	Unit	Today	5 years	5-10 years	20 years
Maximum panel dimension	mm x mm	305 x 460	540 x 610	> 540 x 610	> 540 x 610
Minimum die size	mm x mm	5 x 5	3 x 3	2 x 2	< 2 x 2

APPENDIX B-3K

PASSIVE POLYMER DESIGN RULES

Besides the purely optical rules (e.g., bending radii, only smooth shapes) planar, passive polymer waveguides provide a much wider design freedom compared to fiber-based systems. The optical properties are mainly given by the available material sets. They are very similar to the properties of polymer fibers.

Table 4. Passive planar polymer waveguide roadmap design rule properties

Item	Unit	Today	5 years	5-10 years	20 years
Waveguide type		SM / MM	SM / MM	SM / MM	SM / MM
Waveguide height	µm	5 – 500	2 – 1000	1 – 1000	1 – 1000
Waveguide width	µm	≥ 5	≥ 4	≥ 3	≥ 2
Minimum pitch with no crosstalk for SM waveguides	µm	30	30	25	20
Minimum pitch for smallest waveguide dimension for evanescent coupling	µm	10	8	6	4
Minimum bend radii (NA = 0.2)	mm	18	18	18	18
Crossings		available	available	available	available
Electrical vias through optical layer		available	available	available	available
Optical vias				available	available
Accuracy of waveguide end-position on devices < 20 x 20 mm^2	µm	< ±0.5	< ±0.3	< ±0.1	< ±0.1
Accuracy of waveguide end-position on substrates < 100 x 100 mm^2	µm	< ±2	< ±1	< ±1	< ±1
Accuracy of waveguide end-position on substrates < 300 x 300 mm^2	µm	< ±5	< ±5	< ±2	< ±2

APPENDIX B-3L

PASSIVE POLYMER OPTICAL VIAS

For optical vias there is currently no efficient solution available. An obvious solution is based on two mirrors. Unfortunately, this results in high losses due to the two reflections. The need for optical vias is not urgent, since polymer waveguides support crossings, although this technology still needs to mature more over the next decade. Furthermore, the accuracy of the polymer waveguides will be determined by the available photolithographic tools as smoother waveguide walls and surfaces perform better optically and help reduce attenuation as well as optical scattering.

APPENDIX B-3M

POLYMER WAVEGUIDE MANUFACTURING

Planar polymer waveguide technology is still undergoing development for the fiber optics communications industry. There are a number of commercial applications where passive polymer waveguides have been implemented, however, active polymer modulators are still being developed. For the commercial applications of passive polymer waveguides, the use of standardized process automation tooling is common-place, and furthermore, these tools are similar in design and features to that of the silicon semiconductor industry. Wire bonders, flip-chip bonders, pick and place tools are all similar in function.

The one major difference to the silicon semiconductor industry for passive polymer waveguides is the accuracy of the automation tooling for aligning optical components such as fiber optic cables, optical devices (such as laser diodes, optical modulators, photodetectors etc.), to the polymer waveguides. Multimode tolerances are in the +/- 5 to 10 µm range, and this is typical of automation tooling found in silicon semiconductor industry, however, for single mode passive polymer waveguides, special automation tooling that can handle tolerances down to +/- 0.5 µm are routinely needed. This means that the automation tooling must provide the accuracy for optical alignment, and these tools have tighter alignment specifications.

Over the next 5 years, the number of tools that utilize sub-micron accuracies will increase, together with the improvement of alignment accuracy. Over the next decade alignment tolerances down to 0.1 µm or less will be available, and the major improvement in process automation at these tight dimensions will be pick and place operation speed. A continual improvement in alignment accuracy and speed of pick and place will be the major trend in the 20 year timeframe. A number of the tools today can handle wafer format sizes up to 300mm. This will not change over the roadmap period of 20 years, however, tools will be more able to handle a variety of wafer sizes for different applications.

APPENDIX B-3N

OVERALL POLYMER RELIABILITY AND QUALITY ASSURANCE

Over the next 10 years, there will be a significant amount of work to show end-users more R&QA (reliability and quality assurance) data to support optical polymers in commercial applications. This will be similar to the reliability data set that OLEDs needed to show 1-2 decades ago. In a decade, the number of opportunities for polymer based commercial products that are based both on active and passive materials will increase substantially as much of the R&QA data will have been generated. The general trend will be to increase material reliability and performance in the 20 year timeframe.

APPENDIX B-3O

INTEGRATION WITH LASER DIODES

Polymers in the 5 year timeframe will be fully integrated with laser diodes as part of a photonics integrated circuit (PIC) platform. Laser diodes will be located next to polymer modulators, waveguides and other passive polymer devices for fully optical operation. In the 20 year timeframe there will be many varieties of polymer PIC based circuits based on active and passive polymer technologies. In these polymer PIC based technologies there will be a number of active and passive polymer devices, allowing for aggregation of data rates to reach speeds of 400Gbps, 800Gbps, 1600Gbps, 3.2Tbps, 6.4Tbps and further into multi-Tbps product opportunities. Laser diode reliability and degradation is not considered to be a roadblock when integrated next to active and passive polymer devices. This is because much of the R&QA work for laser diode technology is already mature.

Table 5 covers the key modulator device specifications roadmap for single-mode modulator devices.

Table 5. Active EO polymer roadmap properties

Item	Unit	Today	5 years	5-10 years	20years
Modulator Bandwidth		70-100GHz	200GHz	400GHz	800GHz
Suitable for advanced coding (PAM/QAM)		yes	yes	yes	yes
Device type		Slot	Slot	Slot	Slot
Multi-channel operation		4 channels	10-20 channels	20-40 channels	60-100 channels
Electro-Optic activity range	pm/V	Up to 500 (as reported in literature)	<500	<600	<700
Commerical device EO activity range	pm/V	50-300	150-500	250-600	300-800
Poling range	V/ µm	40-100	40-150	40-200	50-400
Photo-stability power handling	mW	100	200	300	500
Thermal stability (commercial maximum)	C	70-85	85-110	85-120	85-130
Device substrate		Semiconductor	Semiconductor	Semiconductor	Semiconductor
PIC material		Polymer/Silicon	Polymer/Silicon Polymer/III-V material Polymer/Dielectrics	Polymer/Silicon Polymer/III-V material Polymer/Dielectrics Polymer/Sapphire/ SiC	Polymer/Silicon Polymer/III-V material Polymer/Dielectrics Polymer/Sapphire /SiC Polymer/Silicon Heterogeneous
Wafer size	mm	Silicon 150 & 200mm	Silicon 200 & 300mm	Silicon 200 & 300mm	Silicon 200 & 300mm
CMOS compati-bility		Yes	Yes	Yes	Yes

APPENDIX B-3P

TRENDS FOR POLYMER PIC PLATFORMS

Both active and passive polymers have been reviewed for their trends over the next 20years. With active polymers, the trends are towards scalable solutions for data communications that include very high-speed polymer modulators with very low power consumption and low costs. With passive polymers, both single mode and multimode materials and technology show also a strong scalability towards higher polymer photonic integration for printed circuit boards and substates that result in increasing performance and lower cost structures.

APPENDIX B-3Q

ACTIVE ELECTRO-OPTIC POLYMER CHARACTERISTICS

There is growing commercial acceptance for active electro-optic polymers, and over the past decade there have been reliability and stability data published that include telecom industry 10-year lifetimes and GR-468 (Telecordia reliability testing) qualifications. Additionally, even though many active polymers reported in publications show the electro-optic coefficient (r33) to be in the 100-200 pm/V range (Lithium Niobate r33 is approximately 30-40 pm/V), many publications show a potential for polymers to have r33's above 400 pm/V. These values allow for very-low-voltage operation for polymer devices such as Mach Zehnder modulators and opens up the potential for sub-1V high speed modulators in the near future. The table below covers the key material specifications roadmap for single-mode modulator devices.

Table 6. Active planar polymer waveguide roadmap material specification properties.

Item	Unit	Today	5 years	5-10 years	20years
Active material		Chromophore	Chromophore	Chromophore	Chromophore
Host material		Organic polymer	Organic polymer	Organic polymer	Organic polymer
Type of moduator		Mach Zehnder	Mach Zehnder	Mach Zehnder	Mach Zehnder
Modulator device		Slot	Slot	Slot	Slot
Slot structure		Core	Core	Core	Core
Slot plasmonic structure		Core	Core	Core	Core
Core refractive index		1.5-1.7	1.3-1.7	1.1-1.8	1.0– 1.9
Optical loss@ 1310nm	dB/cm	1.0-5.0	1.0-3.5	1.0-2.0	0.5-1.0
Optical loss @1550	dB/cm	1-2.5	1-2.0	1-1.5	0.5-1.0
Resistance against humidity / temperature		2000h @ 85°C / 85% rel h.	3000h @ 85°C / 85% rel h.	4000h @ 85°C / 85% rel h.	5000h@ 85°C / 85% rel h.
Long-term temperature range	°C	0 - 85	0 - 100	0 – 110	0 - 120
Compatible with CMOS manufacturing processes		Yes	Yes	Yes	Yes
Compatible with PCB manufacturing processes		Yes	Yes	Yes	Yes
Standardized testing for polymers		Teng-Man, r_{33}, poling, thermal stability	Teng-Man, r_{33}, poling, thermal stability	Teng-Man, r_{33}, poling, thermal stability	Teng-Man, r_{33}, poling, thermal stability

APPENDIX B-3R

NETOWRK SYSTEM ASPECTS OF ACTIVE POLYMER PICS

As the trend towards increased data rates in fiber communications continues, there is also a need to reduce power consumption as well as decrease the physical size of the transceiver unit or box. This leaves a design criterion that is challenging both from a size, weight, power issue as well as a high speed, and more importantly cost considerations.

Polymers have the advantage of naturally high data rate capacity as seen by a number of publications of results that exceed 100GHz bandwidth. Polymers also have the advantage of meeting the lower power consumption targets through driving high speed Mach-Zehnder modulators with voltage levels significantly below 5V and with polymer slot devices in the sub-2V range.

It is well known that polymer materials typically use a spin-on process, and from a weight standpoint, achieve low weight criteria in data communications. The size of devices can vary, however, by integrating polymer modulators with other photonic devices, the size can be minimized effectively.

Last but not least in the key criteria metrics, polymers have scalability, both in high speed performance, and in lower cost structures needed for competitive pricing of transceivers. While many technologies are struggling today to surpass the 5-10$/Gbps mark (i.e. achieve lower $/Gbps numbers than 5$/Gbps), customers of for example datacenters have made it very clear in public forums over the past 2 years that what is required are transceivers that meet $1/Gbps. This metric is not meaningful unless a data rate is attached, and the metric of $1/Gbps at 800Gbps data rate translates into a data link for a data center where the total transceiver cost must meet $800 ($400 each end of the link) and the data rate for the link must achieve at least 800Gbps. This is certainly a tough challenge, being 10-20X improvement over state of the art today. Clearly, innovation is needed to achieve these types of metrics, and polymers, when integrated into a PIC (photonic integrated circuit) platform have the scalability both to meet and exceed this challenge by the data center companies.

Polymer photonics will grow from up to on average ~10 polymer devices per PIC presently, to over 500 devices per PIC over the next 20 years. The types of PICs that will implement polymers include transmitter that include both modulators, lasers, waveguides, WDMs, spot size converters, and detectors. The functions of these polymer PIC chips may include transmitter drivers, and arrayed transmitter drivers, both incoherent and coherent. Key applications for polymer-based PICs include data communications and telecommunications. Within data communications, both datacenters, and high-performance computing segments. Table 7 covers the key PIC specifications roadmap for circuits using single-mode modulator devices:

Table 7. Active EO polymer roadmap properties when used as an engine for optical fiber optic transceiver platforms

Item	Unit	Today	5 years	5-10 years	20years
Fiber type for links		Single Mode	Single Mode	Single Mode	Single Mode
Data rates for links	Gbps	100	4-800	8-1600	3200
Integrated Photonics (PICs)		Discrete polymer modulators	Laser/Polymer modulator PIC	Fully active/passive polymer PIC	Fully active/passive polymer PIC
Slot modulator voltage level	V	<3	<1	<0.5	<0.3
Power consumption (to transfer a bit per TxRx)	pJ/bit	<20	<10	<6	<4
Power consumption per polymer modulator	pJ/bit	<10	<5	<2	<1
Transciever with Tx and Rx function for links <2km	$/Gbps @800 Gbps	<5-10	<1	<0.5	<0.25
Transciever with Tx and Rx function for links <50m	$/Gbps @800Gbps	<2-3	<0.25	<0.1	<0.05
Number of polymer devices per Tx function on PIC chip	device	10	100	500	1000

APPENDIX B-4

PROCESS SPECIFICATIONS AND CHALLENGES

(Polymer) growth/layer deposition	[unit]	5 years	5-10 years	20years
Layer thickness uniformity	[nm]	100	50	10
Layer thickness reproducibility	[nm]	50	40	30
Layer composition uniformity	[nm]	200	100	50
Layer composition reproducibility	[nm]	100	50	40
Doping concentration uniformity		N/A		
Doping concentration reproducibi		N/A		
Defect density* (in regrowth)	[cm^2]	<1E-6	<1E-5	<1E-4
Strain reproducibility	[cm^2]	<1E-4	<1E-4	<1E-4
Strain uniformity	[cm^2]	<1E-4	<1E-4	<1E-4

Dry etching (polymer materials)	[unit]	5 years	5-10 years	20 years
Side wall roughness	[nm]	<100	<60	<30
Side wall angle	[deg]	<1	<0.5	<0.2
Etch depth reproducibility	[nm]	<100	<60	<30
Etch depth uniformity	[nm]	<100	<80	<60
Selective etch masking layers		10:1	20:1	30:1
Minimal linewidth	[µm]	<1	<0.5	<0.2
Minimal reproducibility	[µm]	<1	<0.5	<0.2
Waveguide width uniformity	[µm]	<1	<0.5	<0.2
Minimum spacing	[nm]	<100	<80	<60
Minimum grating pitch	[nm]	<10	<5	<2
Grating etch step uniformity	[nm]	<10	<5	<2

Wet etching (polymer materials)	[unit]	5 years	5-10 years	20 years
Side wall roughness	[nm]	<20	<10	<5
Side wall angle	[deg]	<10	<5	<2
Etch depth reproducibility	[nm]	<100	<60	<30
Etch depth uniformity	[nm]	<100	<80	<60
Selective etch masking layers		20:1	30:1	40:1
Minimal linewidth	[µm]	<1	<0.5	<0.2
Minimal reproducibility	[µm]	<1	<0.5	<0.2

Waveguide width uniformity	[µm]	**<1**	**<0.5**	**<0.2**
Minimum spacing	[nm]	**<100**	**<80**	**<60**
Minimum grating pitch	[nm]	**<10**	**<5**	**<2**
Grating etch step uniformity	[nm]	**<10**	**<5**	**<2**
Wet etch undercuts	[µm]	**<1**	**<0.5**	**<0.2**

Contact Lithography (polymers)	[unit]	5 years	5-10 years	20 years
Overlay accuracy	[µm]	**<1**	**<0.5**	**<0.2**
Resolution	[µm]	**<1**	**<0.5**	**<0.2**
Required Flatness requirements	[nm]	**<100**	**<50**	**<20**

Stepper/scanner Lithography	[unit]	5 years	5-10 years	20 years
Overlay accuracy	[nm]	**<100**	**<50**	**<20**
Resolution	[nm]	**<100**	**<50**	**<20**
Required Flatness requirements	[nm]	**<20**	**<15**	**<10**

Laser Lithography	[unit]	5 years	5-10 years	20 years
Overlay accuracy	[nm]	**<100**	**<50**	**<20**
Speed	[sec]	**<10**	**<5**	**<1**
Resolution	[nm]	**<20**	**<15**	**<10**
Required Flatness requirements	[nm]	**<100**	**<50**	**<20**

E-BeamLithography	[unit]	5 years	5-10 years	20 years
Overlay accuracy	[nm]	**<10**	**<5**	**<2**
Speed	[sec]	**<100**	**<50**	**<10**
Resolution	[nm]	**<10**	**<5**	**<2**
Required Flatness requirements	[nm]	**<20**	**<15**	**<10**

Annealing	[unit]	5 years	5-10 years	20 years
Temperature@time budget	[K]	<300	<400	<500

Planarization	[unit]	5 years	5-10 years	20 years
Temperature@time budget	[K]	<300	<400	<500
Required flatness	[nm]	**<100**	**<50**	**<20**

Passivation (of polymer)	[unit]	5 years	5-10 years	20 years
Temperature@time budget	[K]	<200	<300	<400

Dicing and cleaving (polymer)	[unit]	5 years	5-10 years	20 years
Position accuracy	[µm]	<2	<1	<0.5

Metal deposition (on to polymer)	**[unit]**	**5 years**	**5-10 years**	**20 years**
Temperature budget	[K]	300	400	500

Wafer bonding	**[unit]**	**5 years**	**5-10 years**	**20 years**
Temperature budget	[K]	300	400	500

APPENDIX B-4A

CRITICAL MILESTONES

Overview of the Critical, Regular and Desirable Milestones

Critical Milestones		
CMx	Content title	Period 5, 10, 20 yr
CM1	200GHz 3dB bandwidth (OE S21)	5
CM2	R33 <500pm/V	5
CM3	Telcordia qualification for commercial use	5
CM4	<2dB/cm optical loss in MZ device for 1200-1600nm	5
CM5	Integration with PICs (both Silicon Photonics and III-V such as InP)	5
CM6	Passive optical loss in waveguide @1310nm <0.2dB/cm	5
CM6	Passive waveguide spectral bandwidth up to 120nm	5
CM8	Passive waveguide NA <0.4	5
CM9		
CM10		

Regular Milestones		
RMx	Content title	Period 5, 10, 20 yr
RM1	100GHz 3dB bandwidth (OE S21)	5
RM2	R33 <300pm/V	5
RM3	Telcordia qualification for commercial use	5
RM4	<2dB/cm optical loss in MZ device for 1200-1600nm	5
RM5	Integration with PICs (both Silicon Photonics and III-V such as InP)	5
RM6	Passive optical loss in waveguide @1310nm <0.2dB/cm	5
RM6	Passive waveguide spectral bandwidth up to 120nm	5
RM8	Passive waveguide NA <0.4	5
RM9		
RM10		

Desirable Milestones		
DMx	Content title	Period 5, 10, 20yr
DM1	400GHz 3dB bandwidth (OE S21)	10
DM2	R33 >500pm/V	10
DM3	Telcordia qualification for commercial use	10
DM4	<1dB/cm optical loss in MZ device for 1200-1600nm	10
DM5	Integration with PICs (both Silicon Photonics and III-V such as InP)	10
DM6	Passive optical loss in waveguide @1310nm <0.1dB/cm	10
DM6	Passive waveguide spectral bandwidth up to 160nm	10
DM8	Passive waveguide NA <0.5	10
DM9		
DM10		