POLYMER MATERIALS TWG

EXECUTIVE SUMMARY

Technology Platform:
Polymer (organic) based technologies for photonic applications have been developed by both academia and industry over the past 40+ years. Both active and passive polymers have been researched, optimized, developed and made into products by a number of companies globally. The key application for photonic based polymers has been fiber optic communications, namely telecommunications, data communications, high performance computing, where fiber optic interconnects and links are utilized. Nevertheless, new avenues are possible for other applications and in other wavelength ranges.

Current Platform Status:
The whole industry today (epitaxial vendors, foundries, various chip suppliers, standards organization, test equipment vendors, package houses) are gearing up for 100 Gbaud with some players stretching their frontier of performance to 120 Gbaud for reach distances up to 100km. Already, in 2020 there are a number of prototype commercial products with 120Gbaud performance at reach lengths up to 100km. The industry is wondering where to go next. The customers - both giant data center companies and the telecommunication companies - are expecting data rates to continue to move quickly beyond 400 Gbps and on to 800 Gbps and even 1600 Gbps.

The obvious, yet most difficult next move is to revisit increasing the optoelectronic device speed, and those speeds in particular that are driven not from 30-40 GHz optical bandwidth, but 80-100+ GHz (typically 40 GHz corresponds to 50 Gbps and 80 GHz corresponds to 100 Gbaud). At the same time, these new optoelectronic devices must be very small, and operate with very low voltage to keep power consumption low.

Today's roadmaps are expressing desire, but at the same time doubts, about getting beyond 100 or 120 Gbaud based on incumbent technologies. Unlike conventional modulator materials such as InP, Lithium Niobate, silicon photonics and GaAs, the polymer material system is naturally fast. Companies such as Lightwave Logic, Inc. are designing commercial high-speed optical modulators made from electro-optic polymers that will be capable of 100 Gbaud and beyond. Technical data showing 130 GHz (corresponding to 150 Gbaud) indicates that even higher speeds should be possible in the future.

Several 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 support new, very cost-effective optical transceiver packages with high optical gate numbers. Polymers are perfectly suited for adiabatic coupling which is the main enabler for silicon photonics – WDM systems.

In polymer based optical fibers (known as polymer optical fiber (POF), optical attenuation is a key metric, and the latest status is now improved in terms of dB/km to be competitive with optical fiber. While POF is larger in diameter to glass fibers, it does not need to be cleaved, and can be installed quickly and efficiently into small networking environments.

Main Roadmap Challenge:
The main roadmap challenge for the communications industry is to plan future data rates that exceed 120Gbaud for reach distances up to 100km. A number of vendors are looking at how to address 200Gbaud, and are planning spatial multimplexing (adding fibers), wavelength division multiplexing, (adding wavelen gths in a single fiber), encoding with more complex symbols per bit (PAM, QAM etc), and lastly, designing optical and electrical devices for higher bandwidth. These higher performance drivers are being pulled by data hungry customers such as data centers, high performance computing, and shorter reach telecommuications.

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.

Industry Needs:
Unlike conventional modulator materials, the polymer material system is naturally fast. Lightwave Logic, Inc. for example is designing commercial high speed optical modulators made from electro-optic polymers that will be capable of 100 Gbaud. Technical data showing 130 GHz (corresponding to 150 Gbaud) indicates even higher speeds should be possible in future.[1] The polymer material system also has the potential of extremely low voltage levels on the order of 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 100Gbaud communications today.

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 quite reasonable to extend the industry roadmap to 120 Gbaud in the next few years, and 200 Gbaud over the next decade.

[1] Source: M. Lebby. [Online]. Available: http://lightwavelogic.com/external.asp?b=2252&from=dl&ID=175125

Needs < 5 years

- Device speed increased (bandwidths EO S21 of 80GHz (polymer modulator) in PIC platform
- Drive voltage at 1V (polymer modulator) so that drivers can be eliminated
- Telcordia qualification for polymer modulators
- Hybrid integration with InP lasers

Needs 5-10 years

- Device speed increased (bandwidths EO S21 to 120GHz+ (polymer modulator) in PIC platform (for 150Gbps NRZ data rate which can be viewed at 150Gbaud)
- Drive voltage less than 1V (polymer modulator) so that drivers can be eliminated (direct drive from CMOS ICs)
- Telcordia qualification and reliability for polymer based modulators
  Full integration with semiconductor platforms

Needs > 20 years

- Device speed increased (bandwidths EO S21 to 150GHz+ (polymer modulator) in PIC platform (for 180Gbps NRZ data rate or 180Gbaud)
- Drive voltage less than 1V (polymer modulator) so that drivers can be eliminated (direct drive from CMOS ICs)
- Telcordia qualification and reliability for polymer based modulators
  Full integration with semiconductor platforms

INTRODUCTION

Polymer (organic) based technologies for optoelectronic and photonic applications have been developed by both academia and industry over the past 40+ years. Both active and passive polymers have been researched, optimized, developed, and made into products by a number of companies globally. In fact, going back to the 1970s, there was strong government funding as can be seen in the figure below for electro-optic and passive organic polymers in USA, Japan, and Europe. In USA, Federal Government agencies such as NSF, DOE and DOD 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 enough, some of the slideware, papers, books, and other technological reports from the 1970s show how polymers could ease the 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).

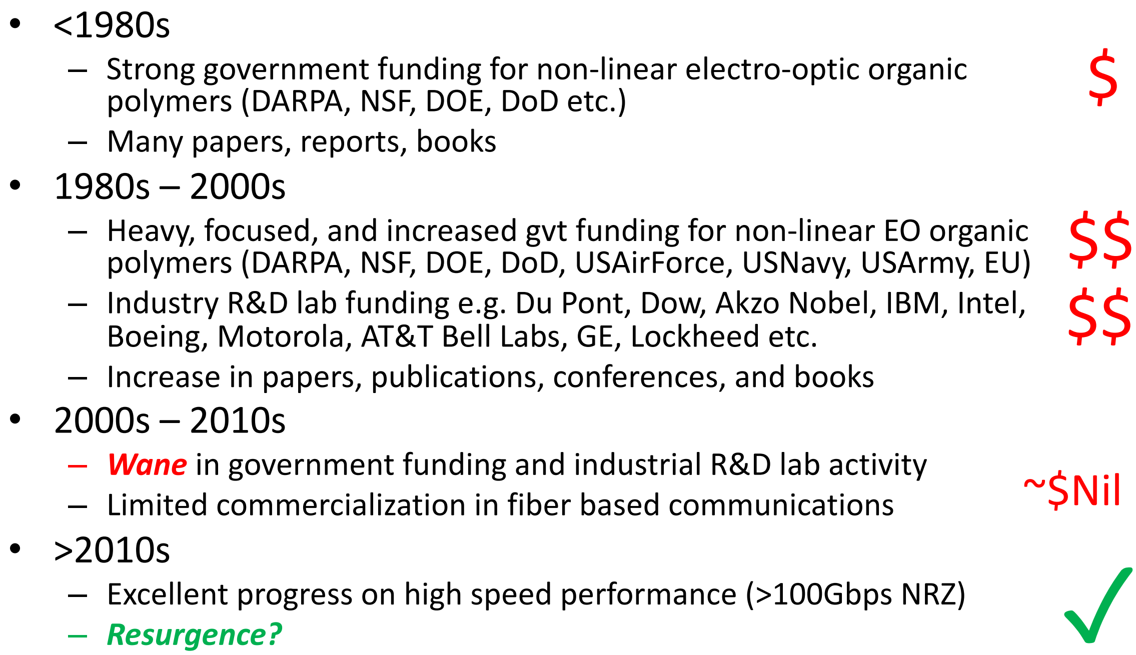

Figure 1. A review of the funding dynamics for polymers over the past 40 years

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. For the next 2 decades, both government agencies and industrial R&D labs increased their output on polymer publications with papers in journals, conference talks and a number of polymer-based books. A number of both active and passive polymer optical technologies included components such as: polymer optical fiber (POF), embedded optical polymer passive components, EO polymer modulators, polymer waveguides, polymer lenses (both diffractive, refractive, and holographic), connectors (especially single and multiple fiber varieties), and simple polymer printed circuit boards (pcb) and other polymer dielectric laminate substrates for high RF performance.

During the 1980s to 2000s, there was an anticipation that polymers would become an exciting new opportunity on a number of fronts and that would enable photonics to move to the next level with photonics integration both at the device level, as well as the board level for both active and passive polymer technologies. The amount of investment is hard to estimate but may have exceeded a few $B during the 80s and 90s timeframe in this field. During the following decade, i.e. 2000s there was a wane in government funding and industrial R&D lab activity, to the point that by the time 2010 approached, almost every program was discontinued. When fiber communications applications are explored, just about every research, development and manufacturing group working on polymers in the 90s and 00s, terminated their programs. Funding dried up, and this left just a few players in the 2010 timeframe who continued their work believing that one of the main funding segments: active EO polymers for photonics will eventually become a technology platform in fiber communications that everyone has wished for over the past 30 or so years. In the meantime, passive polymers have and still continue to experience good commercial success with technology platforms such as POF, 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.

Plastic polymer fiber[2] 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 had niche commercial markets in illumination (where heat generated was low), short distance optical interconnects for automotive applications and instruments. 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 still continues to be owned by copper-based interconnects, especially at link reaches of 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 100Gbaud 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 50Gbps. Plastic optical fiber aperture angle and core diameter is much larger than glass fibers as can be seen in Figure 2 below:

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

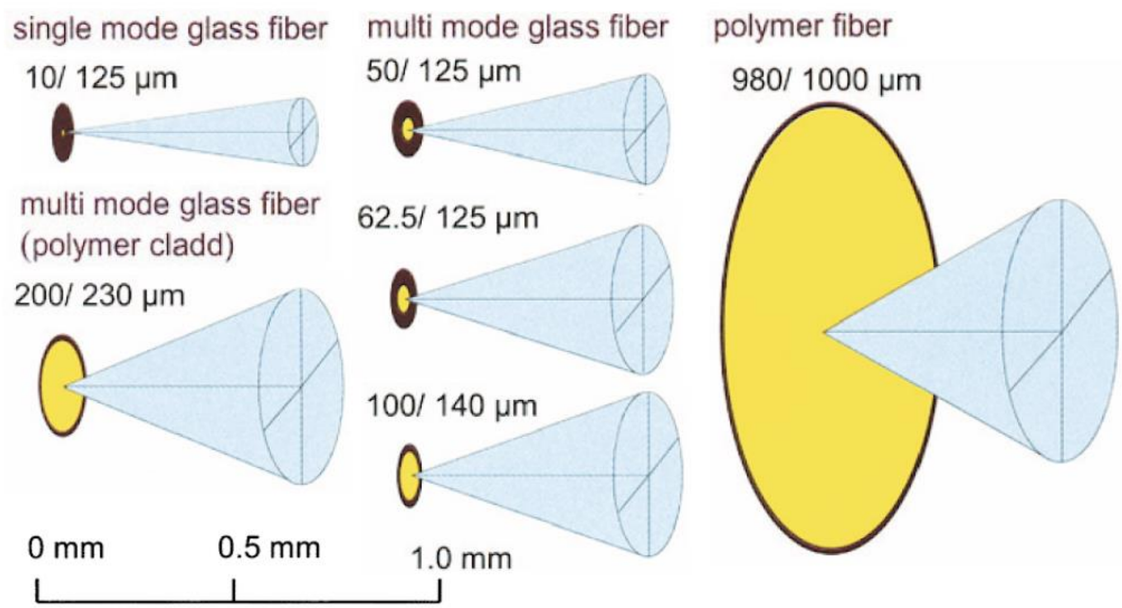

Figure 2 Aperture angle and core diameter of plastic polymer optical fiber verses glass optical fiber in both single mode and multimode varieties.

POF polymer fibers have now improved their attention (dB/km) to be competitive with optical fiber[3], and this is shown in Figure 3 below:

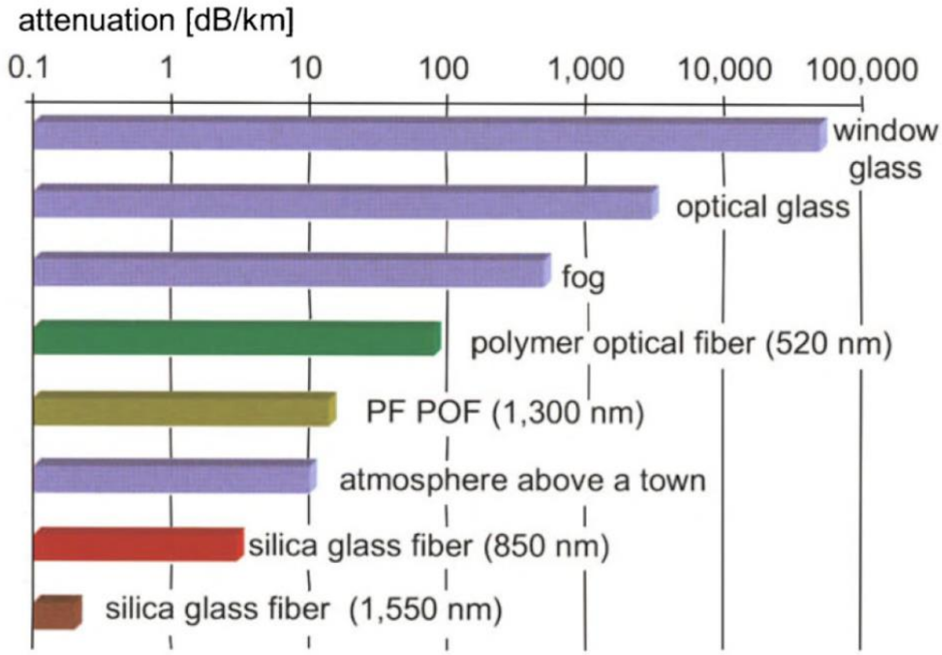

Figure 3 Comparison between different media (glass, polymer) that shows various level so attenuation.

POF has improved significantly over the last 2 decades[4], and Figure 4 below shows the spectral loss in a polymer PMMA step index profile fiber. This wavelength-dependent attenuation curve has three attenuation minima with wavelengths that can be utilized for POF at 520nm (green), 570nm (yellow), and 650nm (red).

[3] POF – Polymer Optical Fiber For Data Communication Applications, Daum, W, et al., Springer (2002).
[4] Fiber Optical Data Communication: Technological Trends and Advances, Edited by Casimer DeCusatis, Academic Press (2002).

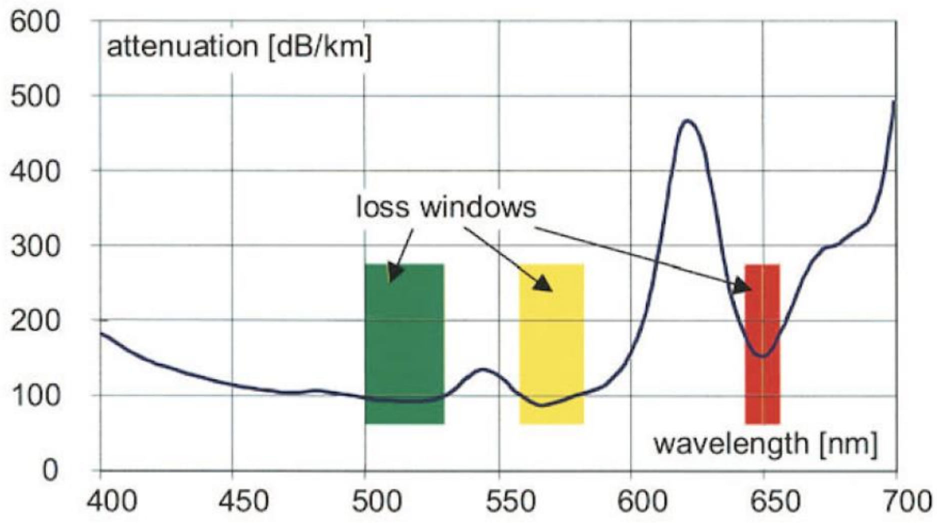

Figure 4 Spectral graph of attenuation in polymer optical fibers.

In the field of active polymers, there have been limited continued progress with programs that have included the University of Washington, University of Texas, University of Arizona, KIT (Germany) and commercial
companies such as Gigoptix (Gigpeak), Br Photonics, and Lightwave Logic. A number of Asian universities have increased their efforts to advance EO active polymer photonics since around 2010, and this leads a resurgence of this technology in the industry. With the natural ability for EO active polymers to be operated at very fast optical switching, optical devices such as modulators have the potential to drive this resurgence quickly into a growth commercial business over the next decade.

Certainly, looking at the performance of electro-optic active polymers in the last decade, the technical speeds achieved now exceed 100 GBaud (with optical bandwidths in the range of 30-40 GHz), with low voltage levels, low power consumption, and plenty of scalability to high performances of 400 Gbps, 800 Gbps, 1600 Gbps and beyond. While the technical outlook for passive polymers is strong, it has been clear that the return on investment for the electro-optic polymer industry has been lower than anticipated over the past few decades, but now as fiber optic applications demand low power, high speed and scalability, the prospects for increased investment in those companies that still provide polymer solutions are increasing quickly.

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.

New areas of interest for polymers include optical polymer wire bonds as can be seen in Figure 5 below where manufacturing techniques are utilized to create free-form optical wire bonds that connect a number of 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.

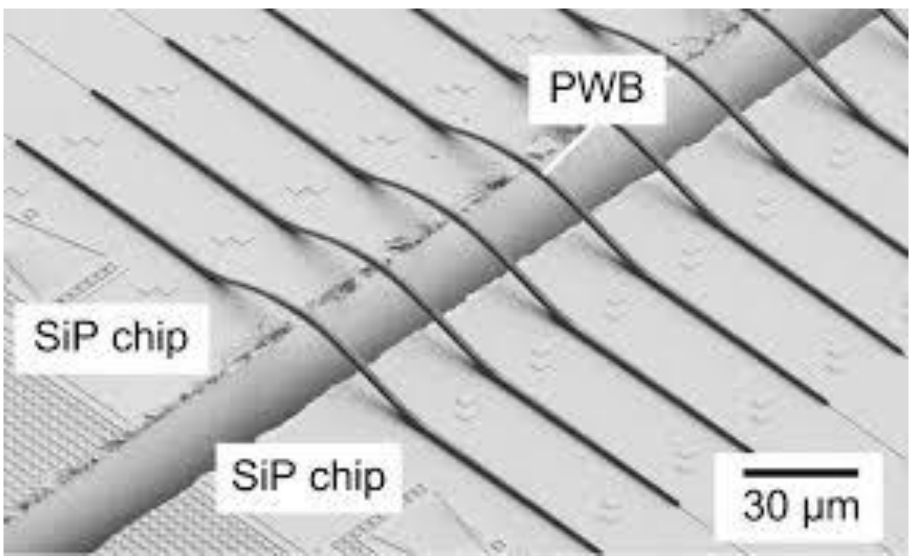

Figure 5 PWB (Polymer wirebonds) are shown to connect optically, two semiconductor chips of silicon photonics[5].

[5] https://www.industrial-lasers.com/micromachining/article/16488493/kit-develops-photonic-wire-bond-for-optical-chip-connections

Other areas of interest are free-form optics that extensively utilizes polymer-based technologies.

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.

A typical example of a freeform polymer lens is show in Figure 6 below:

Figure 6 A typical freeform optical lens that has been manufactured using polymer transparent materials[6].

[6] http://www.gaggione.com/freeform_lenses.xhtml

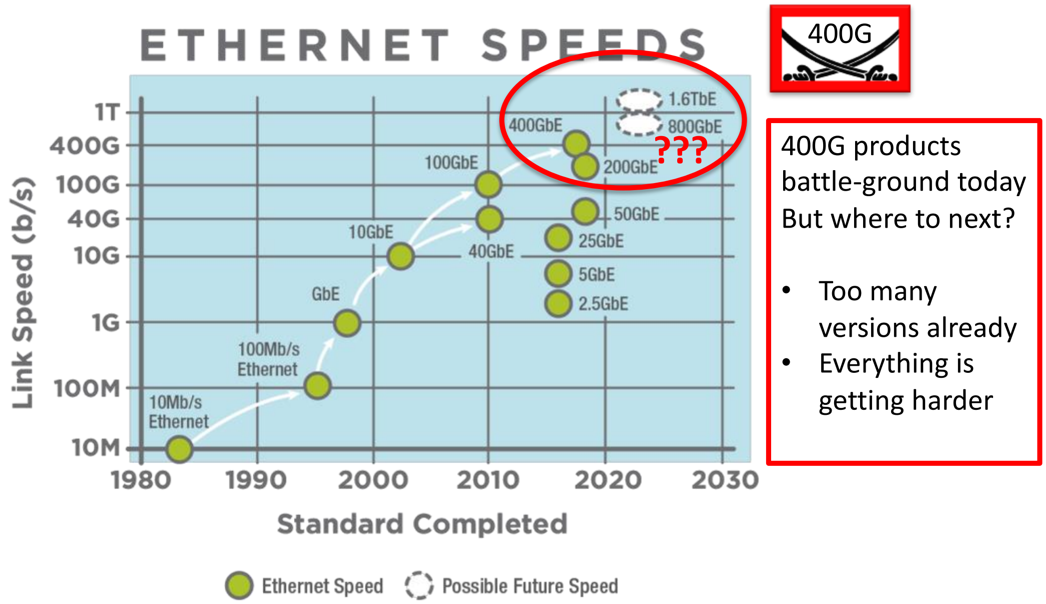

Figure 7. The trend to higher and higher data rates with Ethernet based optical transceivers. Uncertainty exists beyond 400Gbps

As performance increases in the optical network, both electronics and fiber optics have already been forced to rely on some clever innovations to get the industry where it is today. A roadmap by the Ethernet Alliance shows trends out to 2030 for data rates of 800Gbps and 1600Gbps (or 1.6Tbps)[7]. For electronics, multi-core processors, FinFET transistor structures, and specialty processors are some of the ways that the industry has circumvented the difficulty of continuing to shrink transistors. In the past two decades, optoelectronic devices have increased their operating speeds dramatically - but not as much as data rates have increased.

[7] https://ethernetalliance.org/technology/2020-roadmap/ and https://ethernetalliance.org/technology/2019-roadmap/

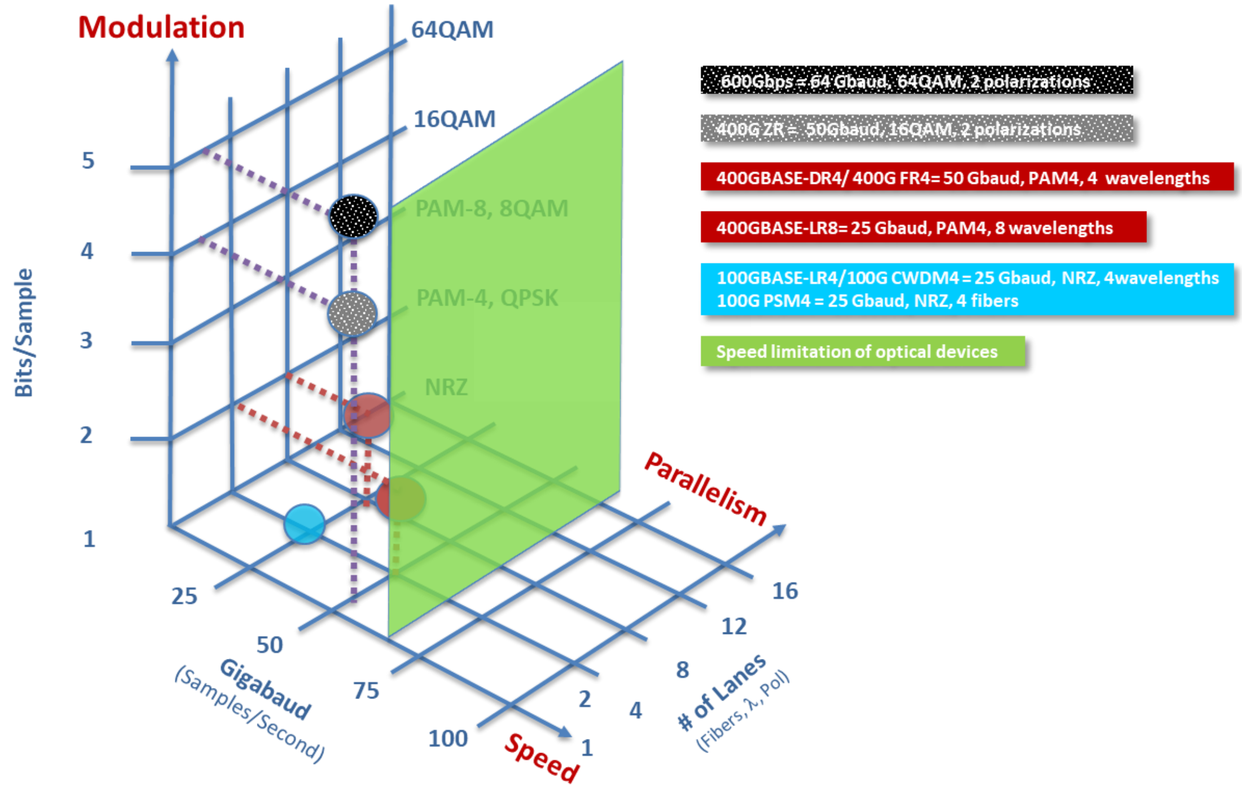

Figure 8. Limited speed has forced the use of complex multi-dimensional transmission schemes

Several popular current and new transmission formats are shown in Figure 8. Notice how complicated and constrained the optics industry has become. This is a result of being constrained by optical device speed to keep to the left side of the green plane. While this graph does focus on the opportunity for EO polymer modulators it does not give due justice to the role passive polymer optics, connectors and lenses have played in supporting, accessory roles for the optical network, and optical interconnects[8].

Figure 9 expands on how and why the industry arrived at the condition shown by the 400Gbps points where different techniques are being utilized to achieve these aggregated data rates[9]. When the industry went from 1 Gbps to 10 Gbps around 2000, progress was a relatively simple matter of developing faster transmitter and receiver devices. It was like pushing down on the accelerator in a car and going faster automatically. Device engineers made lasers go faster and fiber optic links sped up from 1 Gbps to 10Gbps. The industry started at the yellow circle (Figure 9) representing 1 Gbps, then moved along the orange arrow to the orange circle representing 10 Gbps.

[8] https://www.lightwavelogic.com/resource-center/technical-presentations-white-papers/
[9] https://api.mziq.com/mzfilemanager/v2/d/307dbc8b-e212-48ba-9968-8cef3f6b5188/b12c07f7-861a-70a5-295d-47d4cad5bacb?origin=2

But to go from 10 Gbps to 40 Gbps - after an abortive attempt at a simple speed increase in the early 2000's - the industry was forced to use four parallel lanes each at 10 Gbps. This new direction is represented by the purple arrow leading to the purple circle representing 40 Gbps of aggregated data. In some cases, these lanes are separate fibers. In other cases, the lanes are wavelengths carried in the same physical fiber but staying separate from each other (wavelength

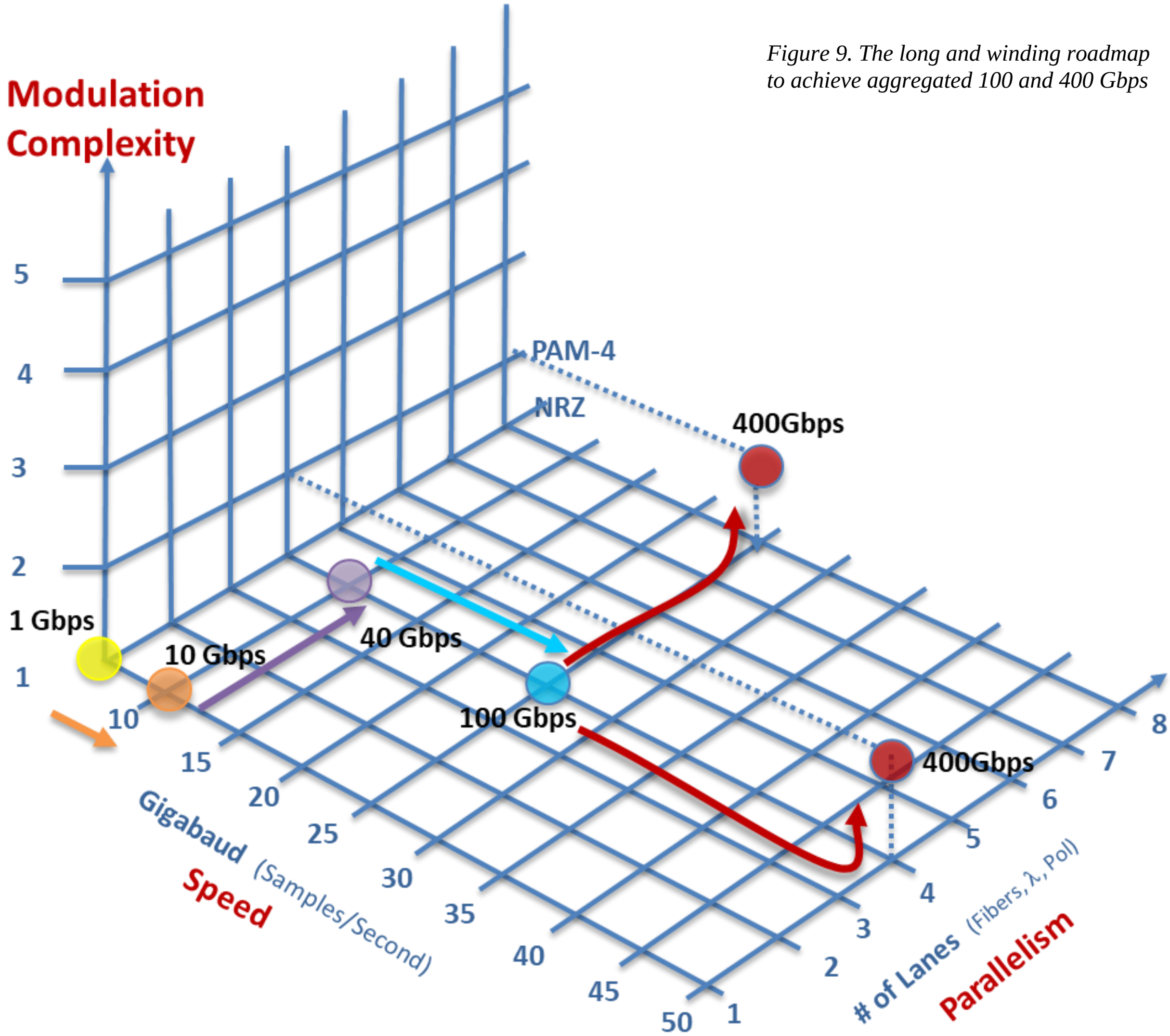

Figure 9. The long and winding roadmap to achieve aggregated 100 and 400 Gbps

division multiplexing or WDM).

By 2015, millions of units of 40 Gbps optics in the form of 4 x 10 Gbps transceivers populated the biggest datacenters. This bought time for the device speeds to progress to 25 Gbps, enabling 100 Gbps still using 4 parallel lanes. The resulting progress as the blue arrow that leads to the blue circle which is 4 lanes x 25 Gbps = 100 Gbps. 100 Gbps using these parallel lanes is where the industry is today with formats such as 100 GBASE-LR4 standardized by IEEE and industry published multi-source agreement specifications for 100G PSM4 and 100G CWDM4. (Looking closely to Figure 9, it can be seen that the speed axis is labelled Gigabaud rather than Gigabits per second. This is explained below.)

Since 2015, appetite for more data is still increasing, and this has challenged the industry to consider an aggregated speed of 400 Gbps. Currently the industry is struggling with yet another directional change as it advances to 400 Gbps. Two popular routes shown in Figure 9 as red arrows both required adding a vertical dimension to the graph. One route utilizes 8 lanes, and the other route utilizes 4 lanes of data. Simple math says that 8 lanes of 25 Gbps only does not get to 400 Gbps: in fact, 4 x 25 = 200 Gbps. So, to double up the speed, there has been another innovation: the vertical axis shows the use of advanced signaling or modulation which is explained next.

The top of Figure 10 shows a data stream of 1's and 0's sent simply as "light" and "no light"—as scheme called NRZ (non-return to zero) or OOK (on-off-keying). It also shows how a transmitter with limited speed blurs the data. However, if data is encoded to be sent as multiple levels, more

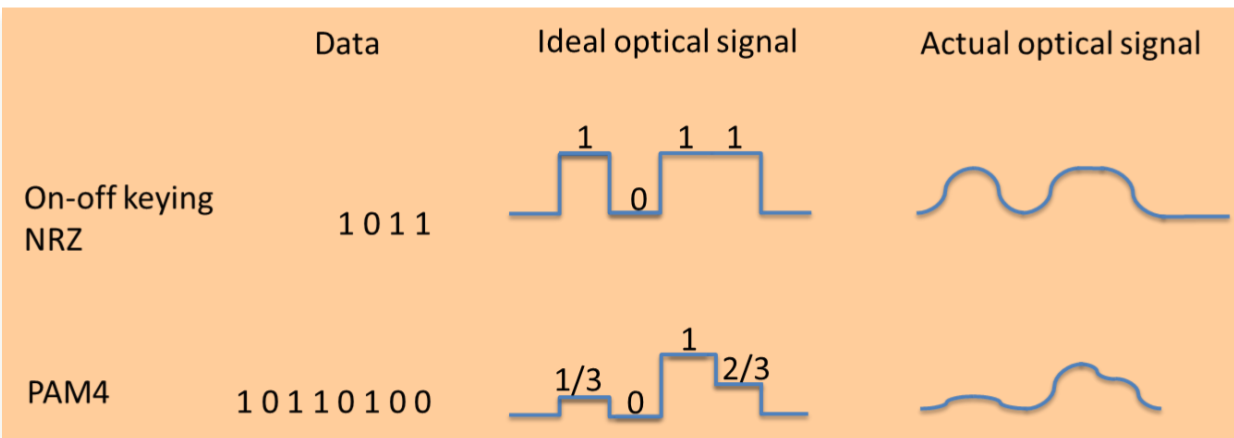

Figure 10. Comparing data modulation schemes

(1) NRZ (non-return to zero) or sometimes referred to as OOK (on-off-keying) is simply 2 levels: 1 and 0

(2) PAM4 (Pulse Amplitude Modulation) uses 4 levels and has the effect of doubling of the data rate

than one bit can be sent in one symbol period, or a faster bitrate (bits/second) than baudrate (symbols/sec).
The lower part of the figure above shows twice as many bits sent using advanced modulation with the same transmitter speed as before. The particular coding illustrated is PAM4 (pulse amplitude modulation, 4 levels) where each pairs of bits are converted to a single symbol ('10' is mapped to 1/3 height signal, '11' is mapped to 0 height signal, etc.). This innovation comes at the cost of quite a lot of complexity in the form of signal processing electronics.

In Figure 10, both ways shown for 400 Gbps rely on this factor of 2 multiplication in bit rate from using PAM4. The two choices are 4 lanes of 50 Gbaud PAM4 (4 lanes x 50 Gbaud x 2 bits/symbol is used for IEEE standard 400GBASE-DR4 and 100G Lambda MSA's specification for 400G-FR4) or 8 lanes of 25 Gbaud with PAM4 (8 lanes x 25 Gbaud x 2 bits/symbol is used in IEEE standard 400GBASE-LR8).

So far, the discussion has been on the history of short, typically Ethernet carrying fiber links such as those found inside enterprise networks and data centers. Figure 9 maps the history of Ethernet optics from 1 Gbps to 400 Gbps. Bigger pipes which aggregate multiple streams of traffic for transmission over longer distances such as between datacenters, have been forced to use even more complex schemes not discussed here. The gray and black textured bubbles in modulation, speed, and parallelism figure illustrate a few of these additional higher order vertical axis modulation schemes used for these longer distances as having a multiplying factor of up to 5 bits/symbol.

These directional changes have not been as straightforward as represented. Why didn't the industry simply continue adding more parallel channels? Additional real-world requirements on cost, size, error rate and electrical power consumption must also be met. The industry struggled to accept the complexity and cost due to multiple lasers and receivers but ultimately the appetite for data outreached technological progress in faster optoelectronic devices. These considerations are already limiting the degree that parallelism and modulation complexity can be used. It gets even harder the further one goes along each axis! Some of the innovations that the industry included have been passive polymer optics based that include polymer pcb's, polymer-based connectors, polymer-based waveguides, and polymer based optical lenses.

Recall that two different solutions for 400G are shown in Figure 9. One reason that multiple solutions exist is discomfort with the use of 8 lanes. Parallelism beyond 4 lanes has not proved economical or small enough previously. But the industry is even more leery of increasing the modulation complexity. Complex modulation schemes are more sensitive to noise and are more error-prone. Notice that in Figure 10 the difference in PAM4 levels is only 1/3 as much as for NRZ. As a result, the optoelectronics on both transmit and receive ends must distinguish between these smaller differences in signal level. They require power-hungry signal processing electronics not only to encode and decode the data but also to offset errors. The industry already has experience with very complex modulations schemes such as those in telecommunications (QAM etc.), and deems them too large, too power-hungry, and way too expensive - in other words, practical only for long haul national backbone networks. Moreover, they are approaching fundamental limits.

The whole industry today (epitaxial vendors, foundries, various chip suppliers, standards organization, test equipment vendors, passive component factories, package houses) are gearing up for 100 Gbaud with some players are stretching their frontier of performance to 120 Gbaud. The industry is wondering where to go next and 100 Gbaud using 80 GHz based optical devices is the next major node in data rates (with PAM4 encoding this will bring the data rates to 200GBaud per lane). The customers - both giant data center companies and the telecommunication companies are expecting aggregated data rates to continue to move quickly beyond 400 Gbps and on to 800Gbps and even 1600Gbps.

The obvious, yet most difficult next move, is to revisit increasing the optoelectronic device speed. At the same time, these new optoelectronic devices must be very small, utilize polymer waveguides and polymer optical lenses, and operate with very low voltage to keep power consumption low. Today's roadmaps are expressing desire but at the same time doubts about getting beyond 100 Gbaud based on incumbent technologies.

Unlike conventional modulator materials, the EO active polymer material system is naturally fast. Lightwave Logic, Inc. for example is designing commercial high-speed optical modulators made from electro-optic polymers that will be capable of 100 Gbaud both at 1550nm as well as 1310nm. The addition of 1310nm will allow the polymer platform to impact both very short reach optical interconnects as well as medium and long reach fiber optic interconnects.

Vario-optics is a Swiss company manufacturing polymer passive waveguides for fiber communications, and the combination of both active and passive polymers offers active roadmap possibilities for future generations of transceiver performance. Product development of 80GHz plus active polymer modulators is taking place today and these innovations align well with arrays of passive polymer waveguides for multi-channel solutions for next generation fiber optic transceivers.

The opportunity for very high analog optical bandwidths are feasible in the near future with active optical polymers. Already, low voltage and analog optical bandwidths of greateer than 100GHz have been achieved. [10] EO active polymer material system also has the potential of for direct drive from CMOS chips, and may eliminate the need for high speed driver chips, which could save the end user money in the bill of materials for a system design.. Additionally, passive 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 for more efficient architectures in optical networking switches and routers. Polymer optical waveguides are shown in Figure 12 below:

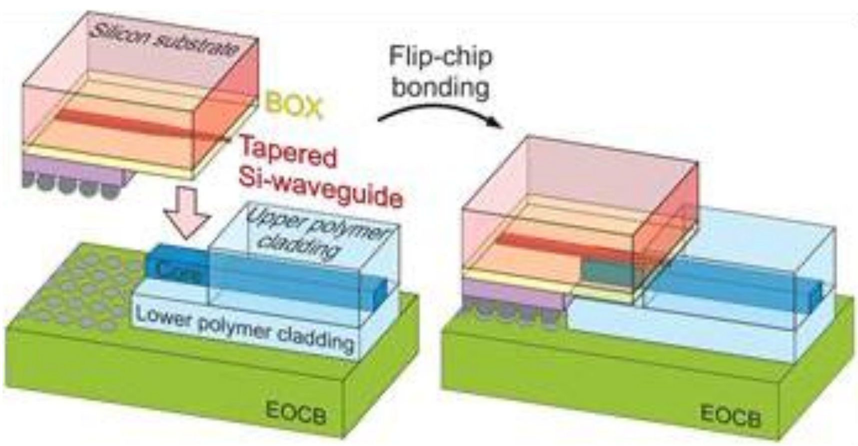

Figure 12: Passive polymer waveguides for interfacing silicon photonics chips[11]

[10] M. Lebby. [Online]. Available: http://lightwavelogic.com/external.asp?b=2252&from=dl&ID=175125
[11] http://wipe.jeppix.eu/public/images/6.pdf

Both passive and active polymer platforms break through technology barriers and they open up new possibilities. Two examples of solutions that could inhabit the new design space are shown in green in Figure 11. The role of passive and active polymers will be able to provide both polymer modulators as well as polymer lenses, waveguides and connectors that will be capable

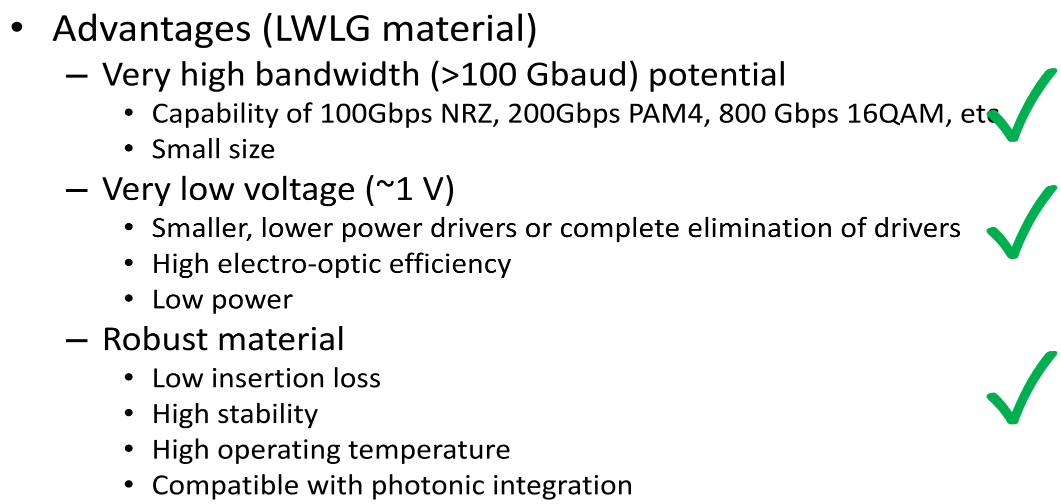

Figure 13. Displaying some of the key advantages of polymer based Mach Zehnder modulators.

of running true NRZ 100, 120 and even 200 Gbaud in the next few years, and possibly 400 Gbaud over the next decade.

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. Figure 13 summarizes key performance attributes for polymer-based Mach Zehnder modulator as well as polymer based optical components such as waveguides, lenses and connectors. Both technologies can be additive to semiconductor technologies such as silicon or III-V compound semiconductors (such as GaAs, InP, III-N etc).

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 14. 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, multiplier or waveguides.

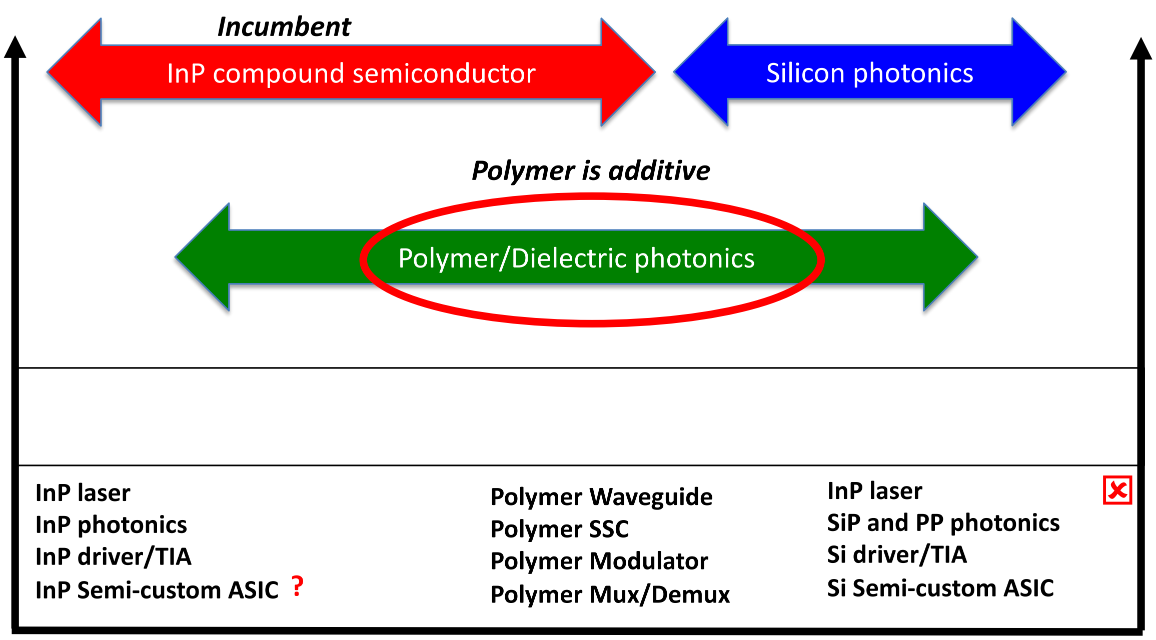

Figure 14. Showing the map of where polymer based technology can be additive to Indium Phosphide (InP) and Silicon photonics (SiP).

One of the key areas that will require strong focus within the polymers segment is standardization. In this segment, the way measurements are taken and are standardized across the industry needs to be improved. For example, the testing and measuring techniques for key metrics such as refractive index, photostability, Teng-Man (r_{33} electro-optic coefficient) testing[12],

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

poling of polymer materials, temperature stability measurements; all need to become more standardized. The trend for polymers to be utilized on a silicon photonics platform has huge potential from a roadmap standpoint as silicon based modulators have difficulty achieving optical analog bandwidths in excess of around 40GHz (50Gbps) today.

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[13]. 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.

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

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

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.

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.

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

Design Rules

Besides the purely optical rules (e.g. bend 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

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.

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.

TEMPERATURE STABILITY

One of the key issues with active polymers has been the temperature of operation. Results over the past two decades have shown that polymers can be fabricated that are temperature stable up to around 85 ^{o}C, and these polymers have demonstrated Telcordia reliability. While the main body of work has this level of temperature performance, other polymers (such as those by Lightwave Logic Inc) have demonstrated temperature stability in excess of 100 ^{o}C in life testing. This new and increased temperature trend will allow active polymers to be applied into a number of applications over and above fiber communications.

RELIABILITY AND QUALITY ASSURANCE

One of the biggest negative perspectives with polymer technology in general is that the material is subject to limited lifetimes and reliability. In fact, this is not true as many polymer-based products that include both active and passive polymers have passed standardized Telcordia testing for reliability and qualification. As shown in Figure 15, polymers have completed

- **Vπ, insertion loss, extinction ratio, and bandwidth measured on all components pre and post test.**
  - HTOL monitored every 500 hours.
- **Visual inspection for hermeticity completed after every test.**
- **Samples size of 11 pieces used for critical tests.**
  - Smaller sample sizes run for mechanical tests due to cost.

Performance Parameter	Maximum Allowable Deviation Caused by Any Test
Vπ	± 0.3 V
Insertion Loss	± 0.5 dB
Extinction Ratio	± 3.0 dB
Bandwidth	± 2.0 GHz

Test Item	Test Description	Specification: Method or Conditions	Sample Data	Passed Y/N
HTOL	High temperature operation life time test	Telcordia GR_468_COREi02 3.3.3.1; 2000 hrs at power, driver, bias and Ta = 85°C	11	Y
Low Temperature Storage	Storage only in low temperature	Telcordia GR_468_COREi02 3.3.2.1 -40°C, 72 Hour	11	Y
Mechanical Shock	Apply mechanical shocks to device	Telcordia GR_468_COREi02 3.3.1.1; mil-std-883 Method 2002.3	7	Y
Vibration	Apply vibration to devices	GR_468_COREi02 3.3.1.1; mil-std-883 Method 2007.2.	6	Y
Thermal Shock	Sudden exposure to extreme changes in temperature	Telcordia GR_468_COREi02 3.3.1.2; mil-std-883 Method 1011.9.	11	Y
Fiber Twist	Twist fiber pigtail	Telcordia GR_468_COREi02 3.3.1.3.1; FOTP 36.	8	Y
Fiber Side Pull	Pull fiber pigtail	Telcordia GR_468_COREi02 3.3.1.3.2; GR-326-CORE 4.4.3.5.	8	Y
Cable Retention	Apply force to the cable	Telcordia GR_468_COREi02 3.3.1.3.3; FOTP 6.	11	Y

Figure 15. Active EO polymers have achieved Telcordia GR-468 standardized reliability testing

Telcordia testing for certain test conditions:

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. There have been a number of examples of active EO polymers achieving Telcordia GR-468 standardized reliability testing, and one example is shown in Figure 15. 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.

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 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		50-100GHz	200GHz	400GHz	800GHz
Suitable for advanced coding (PAM/QAM)		yes	yes	yes	yes
Device type		RWG & Slot	RWG & Slot	RWG & Slot	RWG & Slot
Multi-channel operation		2-4 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	50-150	150-250	250-400	300-500
Poling range	V/ µm	40-80	40-100	40-150	50-200
Photo-stability power handling	mW	25-75	50-100	50-120	100-200
Thermal stability (commercial maxi-mum)	C	60-85	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

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 measured by $/Gbps @ 400Gbps. 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.

ACTIVE POLYMERS (ELECTRO-OPTIC)

Active polymers have experienced a cycle of heavy investment by governments and industry, and then a wane in funding and research. While a few applications such as test, measurement and instrumentation were successful in fully implementing active polymer into products, there was - and still is today - limited commercial acceptance for the technology platform.

- Frequency response is inversely proportional to electrode length
  - Shorter electrode ➡ More Gbps
- **BUT** Vpi is **ALSO** inversely proportional to electrode length
  - Shorter electrode ➡ Larger Vpi
- Only free variable is $\mathbf{r_{33}}$
  - Larger r_{33} ➡ Shorter electrode ➡ More Gbps ➡ Same or Smaller Vpi

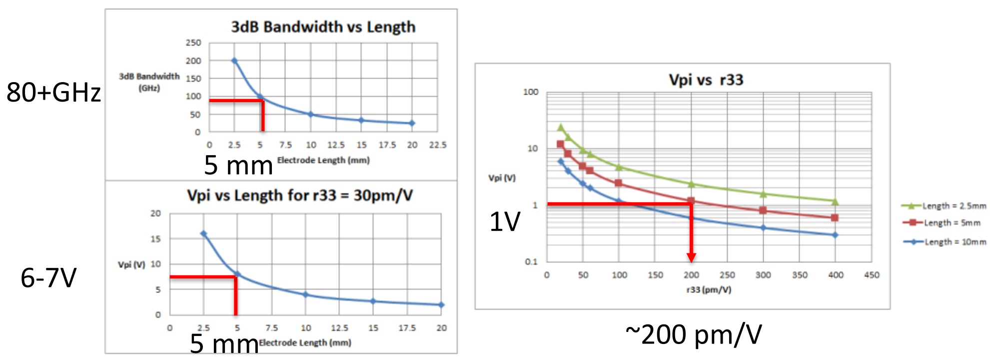

Figure 16. Optical modulator design optimization for small device, low voltage, and high r33 electro-optical coefficient.

It is interesting to note that while there was limited acceptance of active polymers into product platforms, the technology achieved some of the toughest requirements for any new technology - and passed them. For example, active polymers achieved for the 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 (r_{33}) to be in the 30-100 pm/V range (Lithium Niobate r_{33} is approximately 30-40 pm/V), many publications show a potential for polymers to have r_{33}'s above 200, 300 or even 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 100 Gbaud modulators in the near future. This is clearly shown in Figure 16 where high r_{33} is the key for low voltage, miniaturized, high performance polymer modulators.

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		RWG	RWG & Slot	RWG & Slot	RWG & Slot
RWG structure		Core/cladding	Core/cladding	Core/cladding	Core/cladding
Slot structure		Core	Core	Core	Core
RWG Core refractive index		1.5-1.7	1.3-1.7	1.1-1.8	1.0– 1.9
RWG cladding refractive index		1.5-1.7	1.3-1.7	1.1-1.8	1.0– 1.9
Delta between core and cladding for RWG		0.05	0.03	0.02	0.01
Slot 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

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 100 Gbps. 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 in fact with Ridge Waveguide devices in the 1-3V range, and with slot devices in the 0.5-2V 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 a 400Gbps data rate translates into a data link for a data center where the total transceiver cost must meet $400 ($200 each end of the link) and the data rate for the link must achieve at least 400Gbps. This is certainly a tough challenge, being 5-10X 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 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
RWG modulator voltage level	V	<5	<2	<1	<0.5
Slot modulator voltage level	V	<1	<0.75	<0.5	<0.4
Power consumption (to transfer a bit per TxRx)	pJ/bit	<50	<25	<10	<5
Power consumption per polymer modulator	pJ/bit	<10	<5	<2	<1

Transciever with Tx and Rx function for links <2km	$/Gbps @400 Gbps	<5-10	<1	<0.5	<0.25
Transciever with Tx and Rx function for links <50m	$/Gbps @400Gbps	<2-3	<0.25	<0.1	<0.05
Number of polymer devices per Tx function on PIC chip	device	10	100	500	1000

CONTRIBUTORS

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APPENDIX

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*	[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**

* defect in regrowth

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**
wave guide 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**
wave guide 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

CONCLUSIONS

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		