KerrisdaleCapital

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Lightwave Logic, Inc. (LWLG)

A High-Frequency Failure

We are short shares of Lightwave Logic, a $900 million “electro-optic photonic device” company that has been perpetually stuck in “development stage” status for more than thirty years. The company’s stock price rose by 10x in June of last year, in tandem with some well-timed investment conference presentations, excitable message board postings from long-suffering shareholders, and an extremely favorable environment for retail-driven stock frenzies. Since then, Lightwave has been able to maintain at least some of those gains through a NASDAQ uplisting and a steady stream of optimistic press releases touting supposedly successful product tests and patent issuances.

Underneath the façade of accomplishment, though, is almost nothing of substance. Lightwave claims its “products” will enable optical communications speeds 2-3x the current industry standards using a fraction of the power. But Lightwave hasn’t ever come close to commercializing anything: in the 15 years since it’s gone public, it has generated a total of about $6 *thousand* in revenues, which stands in stark contrast to the steady stream of promotional announcements celebrating overhyped prototype completions, product tests, and patents over that time. Somehow, success in the lab – none of which we could find reviewed or published in any of the industry’s scientific journals – hasn’t translated into a single commercial product.

In the same vein, the device specs that Lightwave ambiguously discloses in its announcements and presentations are just not very impressive. The supposed bandwidth capabilities of its stand-alone prototype modulator enable data transmission speeds that are *lower* than those that have been achieved by *entire transceivers* (a much higher hurdle) from prominent industry players like Acacia and Infinera. Furthermore, while Lightwave frequently points out that polymer-based modulators would consume a fraction of the power that standard modulators do, this is completely irrelevant because modulation accounts for less than 5% of the power consumption of a typical transceiver. In other words, even if Lightwave *had* a marketable product, it would be inferior to what is already manufactured in much smaller physical size and at much larger industry scale.

But the most damning detail we discovered about Lightwave’s commercialization efforts is that no one knows how to consistently produce its proprietary polymer. The process of engineering an electro-optic polymer requires the electrical poling of the material in order to freeze its molecular orientation. Based on discussions with engineers formerly at Lightwave, the poling process has been plagued by unpredictable electrical shorts, which decimate manufacturing yields; inconsistent and heterogeneous outcomes within and among the fabricated polymer sheets, which prevent any product standardization; and an unstable final product whose molecular orientation decays over time, dissipating its unique properties. The implication is that *even the mediocre devices Lightwave says it has built and tested are one-off productions that can’t be replicated systematically*.

The sustainability of the spectacle at Lightwave owes a lot to CEO Michael Lebby and the almost blind faith in him shown by the company’s fanatical retail investor base. That faith has been publicly displayed in tens of thousands of InvestorsHub message board posts, where devoted shareholders fervently quote Lebby’s speed/power evangelism as confirmation of the company’s greatness. We think Lebby has tailored a narrative that’s just believable enough to naïve investors, but that falls apart when viewed in the context of the underlying trends in photonics. The company’s grandiose claims about its technology will have turned out to be little more than an optical illusion.

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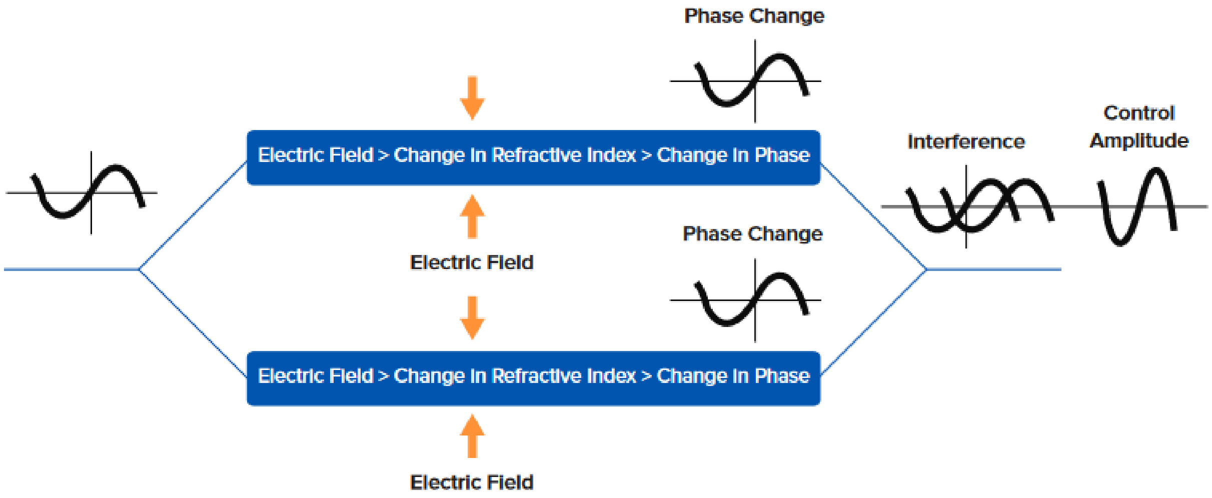
Table of Contents

I. A short primer on optical communications

Much of modern data transmission happens over optical networks: digital data in the form of 1s and 0s are converted into optical signals, which are sent through fiber-optic cables, and are then converted back into digital 1s and 0s on the receiving end. Simplistically, encoding digital data onto optical signals is achieved through directly powering a light source on and off at set intervals, with "on" representing 1s and "off" representing 0s. In optical communications, the laser light source is subject to fundamental physical limits on the speed at which it can be powered on and off, or modulated, without signal distortion.

Instead of direct modulation of the laser driver, lasers typically used in optical communication systems emit continuous wave light, and that light is then modulated *externally* as it travels, in a preconfigured pathway, through specialized material that acts as a kind of precisely controlled high-speed shutter. The shutter encodes the beam with a specific "on/off" wave pattern meant to represent 1s and 0s, similar to the pattern that would have been encoded through direct modulation of the laser driver, but a lot faster (see the diagram below).[1]

Mechanism of a Mach-Zehnder Modulator



The modulator takes light from the laser, and by changing the phase and amplitude, adds the data by using an electric field to change the speed of light (refractive index) passing through the material. Coherent modulators use a Mach-Zehnder design, which splits the light into two arms, changes the phase in one or both arms and then combines them, letting them interfere to control the amplitude. Source: The Advantages of Indium Phosphide Photonic Integration in High-performance Coherent Optics, Infinera

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[1] This is an extremely simplified description of an optical modulator's encoding mechanism. A more detailed explanation can be found from the Purdue University Physics Department here and in slightly more simplified form from Wavelength Electronics here.

The limit on the speed of that shutter is more or less the limit on the speed at which a single symbol, or baud, can be transmitted over an optical network. Presently, the most advanced commercially available optical modulator can operate at a symbol rate of 140GBd (“gigabaud”), or 140 billion symbols/pulses/waves per second. That’s not to say that most data are actually transmitted at that speed; for reasons we discuss below, maximizing the baud rate is not always the most efficient, economical, or even fastest, way to transmit data, but that’s the current limit of what’s commercially possible.

Increasing the baud rate is not the only way to increase the speed of data transmission. In the 1990s, the development of wavelength division multiplexing (WDM) allowed for the transmission of multiple beams of differing wavelengths over a single fiber optic cable without any of the beams interfering with each other. Already in 2000, single optical fibers would carry 48 such channels, and today WDM technology can support more than 200 channels over a single optical fiber. WDM has allowed for orders of magnitude greater quantities of data to be transmitted simultaneously, though each channel requires its own laser source and modulator.

More recently, “coherent” optical transmission techniques have enabled up to 8-fold faster data transmission speed by essentially imprinting information onto the light beam. Light is a form of electromagnetic radiation, propagating in waves through space. These waves have distinct properties including:[2]

- Amplitude, which can be thought of as the “height” of the wave
- Phase, which corresponds to the position of the wave at a particular point in time
- Polarization, which is the geometrical orientation of the wave (is the wave horizontal in space, or vertical, or perhaps moving diagonally?)
- Wavelength/frequency, which describes the length of each wave from peak-to-peak. The shorter the wavelength, the greater the frequency of wave oscillations over a particular interval of time.

In the early days, each transmitted pulse represented either a 1 or a 0, or one bit, which roughly corresponded to either the presence or absence of a wave, respectively. Coherent optics brought to bear powerful digital signal processing (DSP) capabilities to manipulate the amplitude, phase, and polarization of the beam such that each pulse represents not a 1 or a 0, but a pattern of several 1s and 0s. Depending on the DSP technology and modulation algorithm used, each baud, or pulse of light, could now represent up to 8 bits (each bit representing a 1 or 0) of information. To a large degree, advances in optical communications over the past decade have been comprised of improvements in the DSP technology and modulation algorithms that have allowed for more “detailed” encoding (i.e., “higher order” modulation), more precise coherent detection (and error correction) of what’s encoded, and farther reach of each signal.

A standard “optical module” (below) contains the components that carry out all this functionality: the DSP application-specific integrated circuit (ASIC) to turn the digital signal into an analog

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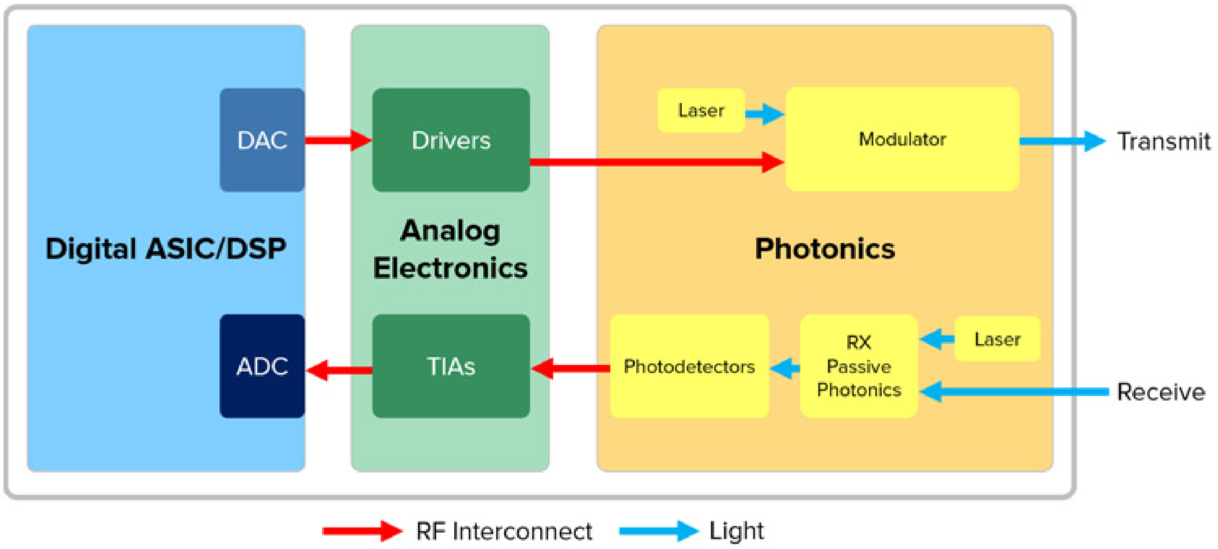
[2] A concise explanation of these properties can be found here.

one, the driver that will interact with the modulator to encode that analog signal, and, of course, the laser and the modulator.

Simplified Coherent Optical Module



Source: Coherent Evolution, ROADMs, and Next-generation IP Networks, Infinera

Shrinking transistor technology and the associated reduction in power consumption have been crucial over this time, allowing for more powerful DSP chips that enable higher order modulation schemes, as well as the joining of all the optical module components in a single package. As the packages have shrunk, the transceiver device, which originally housed the distinct components of the optical module, was able to contain multiple optical modules, each simultaneously transmitting a different wavelength.

Nevertheless, at any given baud rate, because higher order modulation is more susceptible to noise as it travels through fiber, there's an inherent tradeoff between the bit rate and the distance the signals can travel without becoming overly noisy and distorted. The frontier of that tradeoff has been pushed almost to its maximum: the improvements in bit rate enabled by coherent optics have been mostly exhausted as the speed and capacity enabled by higher order modulation have approached the "Shannon Limit," which describes the theoretical capacity limits of a communication medium given the signal quality and available bandwidth.[3]

Increasing baud rates is one way to move beyond the current frontier, and the only way to do that is through more capable modulators. In theory, that's what Lightwave Logic's technology is supposed to do, but before we explain why it can't and won't (and why it probably doesn't matter anyway), it's worth understanding the basic mechanism of optical modulation. As described

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[3] An in-depth discussion of information theory is beyond the scope of this report, but Ciena has published a good description of the Shannon Limit as applied to optical communications.

previously, a laser shoots a continuous beam, and the modulator acts as a rapid shutter, or on/off switch, that encodes a particular pattern onto the beam. That shutter action is a function of the electro-optic (EO) effect, which is a *temporary* change in the speed at which light travels through a material (the refractive index) caused by an electric field. In some materials, the change in refractive index is linearly related to the electric field applied to the material, which conveniently allows for precise adjustments to the speed of light through the material.[4]

In the context of an optical modulator, that material has historically been something like Lithium Niobate (LiNbO), which was cut and placed between two electrodes that would rapidly apply electric fields to the material in a distinct pattern (as in the diagram on page 3). The speed of the beam traveling through the material would dynamically change in response, encoding a precise wave pattern onto the beam. More recently, as silicon photonics methods have enabled the use of silicon in the fabrication of much of the optical module, silicon and indium phosphide (InP) have been used as the modulator materials.[5]

In the mid-1980s, prior to the application of WDM to fiber optic networks, and much before the technological leaps in the performance of optical components enabled by coherent optics and silicon photonics, it seemed like the only way to increase bandwidth was to find materials that would increase the “shutter speed” of the EO modulator. Over time, several academic groups began working on fabricating advanced polymers (basically, plastics) in the pursuit of improving modulator speeds. Many of these labs successfully created polymers that, when tested in a lab setting, resulted in optical modulation speeds that were much faster than those demonstrated by even the most state-of-the-art LiNbO-based modulators. In theory, these materials could enable baud rates 3-5 times greater than could be attained with legacy crystalline materials like LiNbO.

But attempts to commercialize the technology failed miserably. The most famous of these was Lumera, which began as a subsidiary of Microvision in 2000 and went public in 2004. In its 4 years as a public company, Lumera claimed to have “designed and manufactured polymer-based EO modulators that operate at data rates up to 100Gbps [gigabits-per-second],” but the company never generated any material product revenue.[6] In 2008, Lumera merged into GigOptix, another company with negligible revenues operating in the optical space. Three years later, GigOptix announced a successful test of a polymer-based modulator, but by the time the company sold itself to IDT in 2016, the word “polymer” couldn’t be found in its annual report and the company by then had moved on to enterprise video applications.

Based on our exhaustive discussions with a variety of optical components experts, including former Lightwave scientists and materials engineers currently working on new polymer formulations, we don’t think much has changed in the arena of EO polymers. If anything, the advances in other areas of optical communications make EO polymers less relevant than ever. We expect Lightwave’s fate will closely resemble the disappearance of Lumera.

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[4] This is also called the Pockels effect.

[5] As in Acacia Communications’ (a subsidiary of Cisco) designs.

[6] See Lumera’s 2007 10-K

II. Lightwave's polymer "technology" is behind the curve and the feasibility of a manufacturing process to commercialize it may never be achieved

Much of the skeptical investor discourse surrounding Lightwave has focused on the company's history of paid stock promotion, management turnover, zero revenue, and its consistent track record of not delivering on its promises. All of those are true, but they don't seem to dent the optimism of the company's most ardent devotees, who are convinced that Lightwave's polymer technology will (or at least *can*) enable a paradigm shift in data transmission predicated on:

- Faster transmission speeds (2-3x faster than modulators using crystalline materials like LiNbO or Indium Phosphide).
- Reduced power consumption – typically expressed by Lightwave fans as the *10x* lower bias voltage (i.e., the minimum voltage needed to operate) required for a polymer modulator.

For the die-hard fans, no number of corporate red flags can counteract the holy grail of faster speeds and lower power. The problem for those fans is that, in terms of speed, Lightwave's technology *lags* the most cutting-edge offerings from major optical players like Acacia, Infinera, and Ciena, and in terms of power, modulator power consumption is irrelevant:

- Speed: It's worth pointing out here that Lightwave does not have a single spec sheet on its website for any device. The company also has not linked to a single scientific publication related to its research, and we couldn't find any in our search, which makes its device claims difficult to accept at face value. This is in stark contrast to academic labs that frequently publish data on materials they fabricate, as well as private companies like NLM Photonics and Polariton, both of which are focused on polymer photonic applications, and both of which publish prolifically.

  Nevertheless, in its recent annual shareholder meeting presentation (page 43), Lightwave claims that it is the process of "testing…Polymer Plus™ foundry chips" capable of 70GHz bandwidths. It's not clear what kind of "chips" these are – are they the small piece of polymer in the modulator? Are they the complete photonic chip portion of the optical module, which includes a modulator, laser, and photodetector? It's not clear, especially because the next line says that "prototypes…are in progress," which suggests no developed product just yet. But even if we generously assume that Lightwave built sort of optical modulator capable of transmitting at 70GHz, the baud rate associated with a 70GHz-bandwidth modulator in near-optimal conditions is generally a bit over 100GBd.[7]

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[7] Under perfect conditions, the baud rate enabled by a particular bandwidth is double the bandwidth. But conditions are never perfect, so baud rates tend to be lower than the theoretical maximum. In a study of a polymer-based 68GHz-bandwidth modulator they fabricated, scientists at Kyushu University achieved a data rate of 120 gigabits/sec (Gbit/s) with no higher order modulation (i.e., the bit rate and baud rate were equivalent), and 100GBd with higher order modulation. A survey of other polymer-based modulators in

Somewhat consistent with this, earlier this year Polariton announced that it tested a modulator it built using Lightwave's EO polymer *materials*, and that in those tests it achieved 100Gbps with no higher order modulation, which implies a 100GBd speed.[8] But that modulator *was not built by Lightwave* but by Polariton using Lightwave materials, and the test was run as an experiment for 70 minutes, which is not exactly the kind of durability necessary for an optical device that's continuously operating for years in, say, a datacenter.[9]

Anyhow, these speeds are *not particularly impressive*. Acacia recently introduced a full optical module capable of 140GBd/s speeds, which is noteworthy because that's a real-world spec of an entire optical module manufactured on silicon, at scale. By contrast, speed specs on polymer-based modulators (including officially published ones from Polariton) are theoretical capabilities of a stand-alone modulator *before* being assembled into a full optical module. It is inevitably the case that the imperfect connections between the different sub-components of the optical module constrain the baud rate of the device to a level that's lower, sometimes significantly, than the theoretical potential of the modulator. The 100-GBd threshold has also recently been crossed by Infinera and NeoPhotonics (which was recently acquired by Lumentum).

- Power: It's absolutely true that a perfect polymer modulator would consume less than 10% of the power that the InP or silicon versions do currently.[10] On the other hand, it's also *completely irrelevant*. Below is the approximate power consumption breakdown among the different sub-components in the latest generation standard optical module. The modulator on its own is responsible for about 1% of total power consumption, though that might rise to almost 5% if we include the portion of driver power that's used to drive the modulator. The overwhelming majority of power consumption in optical communication devices comes from the DSP circuitry and the laser, which are responsible for coherent modulation functionality and the light beam, respectively. Even bringing down the modulator's power consumption to zero wouldn't make much of a dent.

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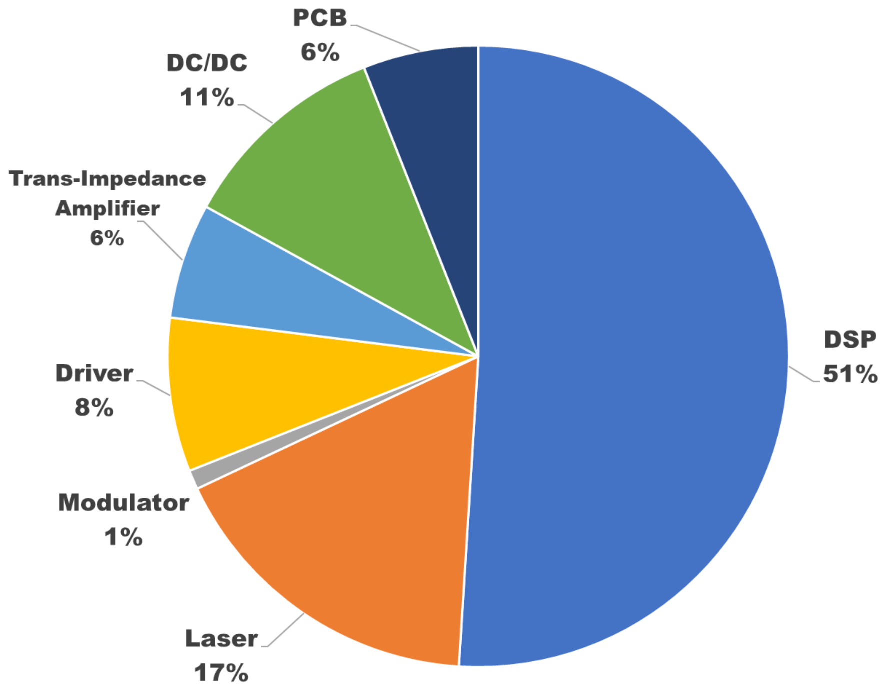
that study found that baud rates tended to be a lot lower than the theoretical maximum, even under optimal conditions. In other words, we're giving Lightwave a lot of credit here.

[8] As we discuss below, there's very good reason to doubt Lightwave's ability to actually manufacture the EO polymer material with any sort of consistency.

[9] In that same ASM presentation, Lightwave embeds slides on page 40 that depict a Polariton modulator capable of 220Gbd, which was at the time a world record speed. In what can charitably be called sleight of hand, CEO Michael Lebby described the result as Polariton "coming up with a world record using out [Lightwave's] material." But that's not really true. Polariton made *its own* polymer using Lightwave's chromophores (which we discuss below). So the world-record modulator speed (which has since been matched by Huawei with an InP modulator) was achieved with a *Polariton* modulator, built using a *Polariton*-fabricated polymer, which was doped with Lightwave's chromophores. As we explain below, chromophores are not particularly difficult to produce. The value-add in modulator construction comes from fabricating the EO material and designing the modulator, neither of which involved Lightwave in this situation. Though that didn't stop Lightwave from conflating the facts and taking credit for it.

[10] Though it's worth noting that Lightwave's supposed Polymer Plus™ foundry chips consume about half the power of industry-standard modulators, not 1/10th.

400ZR Module Power Estimate



Source: *Performance oriented DSP design for flexible coherent transmission, Chris Fludger, Infinera*

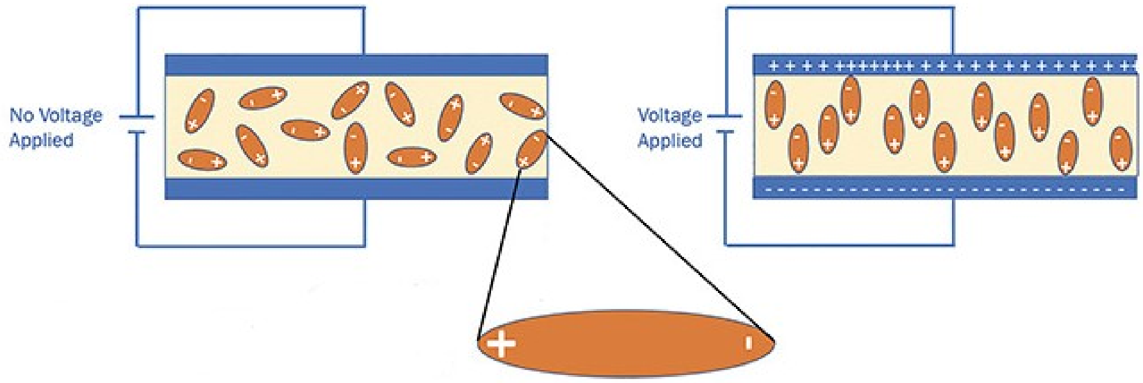
In sum, while the existence of a Lightwave optical modulator is uncertain, the speed of its "chips" (a prototype of which is still in progress) is inferior to what's commercially available off the shelf, and its power advantage is totally immaterial.

Production of EO polymers is more art than science, and Lightwave has never achieved a repeatable or consistent manufacturing process

Perhaps even more worrying for Lightwave's investors should be that, based on conversations with former employees with knowledge of the polymer production details, the polymer manufacturing process remains inscrutable. In other words, Lightwave can't manufacture more than a small amount of the material *because it doesn't know how to.*

As briefly described above, the idea of producing an electro-optic polymer, or a polymer that can induce the electro-optic effect, is almost 40 years old. The process begins by taking an ordinary polymer and doping it with chromophores, which are specialized molecules that absorb particular wavelengths of light. But in order for the polymer to exhibit the EO effect, the actual chromophore molecules must be non-symmetrically oriented, or affixed in the polymer such that all the positive ends of the chromophores are aligned to one side and all the negative ends aligned to the opposite side, as in the diagram below.

Random vs Non-symmetric alignment of Chromophores



The chromophores are normally randomly aligned, but after a poling voltage is applied, the molecules theoretically align in a non-symmetric configuration
Source: Electro-Optic Polymers Improve Speed and Power Efficiency, Lightwave White Paper in Photonics Spectra

But that alignment is not the natural state of these chromophores, which tend to align randomly. So to affix the molecules appropriately, the now-doped polymer needs to be electrically poled. The poling involves heating up the polymer until it's soft, at which point a large electric field is applied to the material, which causes the chromophores to align non-symmetrically. The polymer is then rapidly cooled down so that the chromophores are "trapped" in the alignment that enables the polymer to exhibit the EO effect.

The key steps of the process are fabrication of the material, especially the *design and development* of the chromophores, and the poling, which is surprisingly difficult, and is the sticking point that has held back research in the field since its early days. We have no idea how Lightwave makes its chromophores because, as mentioned earlier, they don't publish any experiments or data. Their only competitor in the field of EO polymers, NLM Photonics, lists 10 different studies conducted by its scientists describing different aspects of the chromophore design process. Suffice it to say that while it's a highly complex task, many labs have published their techniques and methodologies so it's surprising that Lightwave has never explained what sets its chromophore design process apart. We think the fact that NLM's experimental polymers are capable of bandwidths more than 5 times those advertised by Lightwave in its devices is indicative of an antiquated and inferior chromophore design capability at the latter.[11]

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[11] NLM's Director of Materials Development was part of a study that developed a 70GHz modulator back in 2015, which is what Lightwave is apparently capable of 7 years later. In 2019, he was involved in a study that demonstrated a modulator capable of 500GHz in bandwidth.

But even giving Lightwave the benefit of the doubt on its chromophores,[12] based on discussions with former engineers at the company it seems like Lightwave has simply been unable to execute the poling step with any sort of proficiency. There are essentially two problems:

- Fabrication: a lot can go wrong with the actual poling, which involves the application of massive electric fields on the order of hundreds of volts per micron of polymer. One problem that has plagued Lightwave has been unpredictable electrical shorts, which destroy an entire wafer when they happen and result in dramatically lower fabrication yields. Another problem has been that the poling step has heterogeneous outcomes both within the same piece of material, and between different polymer sheets, because the applied electric field isn't distributed evenly across the polymer. As a result, Lightwave hasn't been able to achieve any consistency in specifications – including basic parameters like driving voltage and optical loss – from device to device.

- Stabilization: Lightwave has been unable to execute the poling step in a way that results in a stable material. The poling is meant to *overcome* the molecules' natural (thermodynamic minimum) state of random orientation, and if it's not executed optimally, then the molecules will slowly reorient themselves into a random configuration, which of course renders the material useless from an electro-optic standpoint.

As one former Lightwave engineer told us:

> …this is 100% art and not science. The poling step is fraught. It would be one thing if we knew what was going on when we put these high fields across the materials in these devices, but it's not well-understood. Doing that at scale and trying to understand the failure mechanisms is almost impossible and there's a lot of work to do before one can do that with any confidence. Can you build a handful of devices? Sure. You can get some hero results in the ones that you can get a really high field on, **for reasons you don't even understand**, but that certainly doesn't mean you can build a million of them. [emphasis added]

This is precisely why shareholder confidence in a Lightwave "foundry deal" announcement that's going to "kill the shorts" is badly misplaced (we discuss this, and other shareholder misconceptions below). Lightwave hasn't even figured out how to fabricate their EO polymer in small batches consistently and homogeneously and at an acceptable yield. There's obviously no way they can formalize and qualify a poling technique, let alone effectively relay that process to a semiconductor fab, which would undoubtedly be reticent about using expensive and highly specialized equipment with materials that are not normally part of the chip fabrication process.

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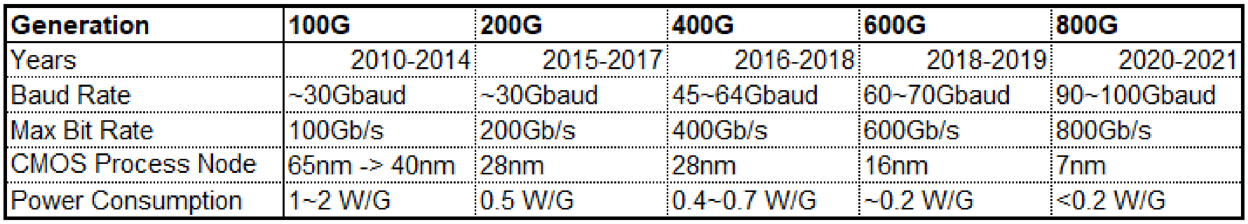
[12] Lightwave announced in September of 2021 that Polariton had built a modulator, which operated at a bandwidth of 110GHz, using materials that were doped with chromophores provided by Lightwave. The actual EO polymer was manufactured by Polariton, as was the modulator.

Other optical experts with whom we spoke suggested that it's precisely the poling problem that has held back EO polymer research over the last 30 years. NLM's scientists have published several studies on the poling step, and have even gone back and tried to expressly engineer chromophores for the ability to be effectively poled. We spoke to some of the NLM engineers, and they have seemingly devised ways to solve for these problems in small batches, but have yet to execute it at the combination of scale and small form-factor that's necessary for a design win from one of the larger industry players. Historically, many of these players – including Cisco and IBM – had their own EO polymer research programs, and all were shuttered for this reason. We should also note that optical experts with whom we consulted were unanimous in their view that because of the material's reputation of continuous failure, even if someone got it to work – and nobody has yet come close – it would take years to earn broad acceptance. There is no foundry deal – and no revenues – anywhere on the horizon for Lightwave.

Electro-optic Polymers will probably never be more than an obscure niche

The optical communications environment in which Lightwave finds itself at present is very different than the one in which Fred Goetz operated 30 years ago when he founded Lightwave's predecessor company, PSI-TEC. The impetus for EO polymers to speed up modulators and reduce power consumption is just not as strong. Even compared to 15 years ago (when Lightwave went public), data transmission speeds enabled by the latest generation of transceivers are 20x the 40Gbps that was standard then, and the devices are substantially smaller and consume 1/20th of the power per Gbps (see the bottom row on the table below). In that context, the 2-3x improvement in transmission speeds that EO polymers would enable just isn't as revolutionary as it once seemed.

The Evolution of High-End Coherent Generations



Generation	100G	200G	400G	600G	800G
Years	2010-2014	2015-2017	2016-2018	2018-2019	2020-2021
Baud Rate	~30Gbaud	~30Gbaud	45~64Gbaud	60~70Gbaud	90~100Gbaud
Max Bit Rate	100Gb/s	200Gb/s	400Gb/s	600Gb/s	800Gb/s
CMOS Process Node	65nm -> 40nm	28nm	28nm	16nm	7nm
Power Consumption	1~2 W/G	0.5 W/G	0.4~0.7 W/G	~0.2 W/G	<0.2 W/G

As the baud rate has tripled in the past decade, the bit rate has increased by a factor of 8 due to higher order modulation schemes. In the meantime, as semiconductor manufacturing processes (the CMOS process node) have advanced and transistors have continued to shrink, power consumption – as quantified by watts per bit/second have come down by a factor of 5-10.

Source: Kerrisdale analysis, Moore and Shannon: A Tale of Two Laws, *by Paul Momtahan, Infinera*

Those improvements were made possible by the symbiotic evolution of silicon photonics and coherent optics. The advanced DSP integrated circuit (a product of silicon semiconductor design and manufacturing) at the core of the modern optical module enabled both coherent modulation and adequate signal clarity at high baud rates. Additionally, as more of the optical module's components were "siliconized," much of the device could be incorporated into a CMOS (silicon semiconductor) fabrication process. That allowed module design to exploit the benefits of miniaturization, co-packaging of the components, and tighter component integration, which further improved speed and power consumption.[13]

But a major contention of EO polymer believers is that *going forward*, due to the industry having come close to the Shannon Limit, baud rates will be the only variable left on which to optimize, and an efficient way with which to increase them is to ramp up the modulator speed with EO polymers. Aside from the difficulties (impossibilities?) we discussed previously that have prevented any substantial commercialization of EO polymers, it's not even clear that the optical industry – and its customers – are very keen on higher baud rates. Various interviews with customers and optical vendors suggest a widespread preference to further exploit parallelism (see below) rather than pursue higher baud rates in order to increase data speeds, for a variety of reasons:

- Commensurate need to improve the electronics – The optical module is a combination of electronic components (mainly the DSP) and optical components (the laser and modulator). If the optics transmit at double the baud rate, the DSP will have to work at those speeds too, and there seem to be significant limitations on the DSP's analog-to-digital conversion speeds such that at the 200GBd rate signal clarity begins to degrade markedly.

- Channel capacity issues – the higher the baud rate, the higher the frequency of the wave being beamed. In isolation this isn't much of a problem, but in a network that's trying to maximize the number of wavelengths traveling over the fiber (i.e., wavelength division), higher frequency wavelengths occupy more spectrum, which can severely limit the number of channels available. For example, a typical network design will allocate 64 different 75GHz-wide channels (for a total of 4.8THz in spectrum). Anything up to just less than 75GBd will fit in those channels, but if the baud rate goes up to 100GBd, the frequency of the wave will be ~100GHz, and each wave will have to take up 2 channels. So while speed has increased by a third, the fiber capacity declined by half, more than offsetting those gains. The problem with increasing baud rates from the current industry maximum (of 100+ GBd) is obvious: the ability to maximize the full spectrum capacity afforded by the fiber can decline precipitously.

- Flexibility of parallel designs – in line with the previous point, lower baud rates with narrower channels can occupy the same, or more, total spectrum, while giving network operators more flexibility. The same data can be sent in a single wave at, say, 200GBd or split into two wavelengths each transmitting at 100GBd. The result is the same, but the latter option gives the network operator more flexibility in which data it routes and at what total speeds.

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[13] Silicon photonics allowed the optical communications industry to "appropriate" semiconductor fabrication tricks pioneered by the electronic integrated circuit makers. The miniaturization and tight integration within the module "package" also allows for a higher achievable baud rate. Acacia has published a whitepaper that elaborates on this.

This is not to say that there is no use at all for higher baud rates. At a given bit speed, higher baud rates allow for farther reach, and higher baud rates may also be useful in applications where spectral efficiency isn't a priority. But there's a good reason why a senior executive at Infinera "believes that the industry is fast approaching the point where upping the symbol rate will no longer make sense…Instead, coherent engines will embrace parallel-channel designs." What this means for EO polymers is that even if they were commercialized tomorrow, it's not obvious they'd be used very extensively.

III. Lightwave has a history of overpromising and never delivering, but benefits from delusional shareholder-fans that always think "it's different this time"

Lightwave has an extremely consistent track record of overpromising and not delivering. A quick tour through 15+ years of press releases and shareholder letters reveals some questionable patterns:

> **Prototype announcements:** Lightwave first anticipated a "prototype fiber optic modulator" in April of 2008 and an "initial prototype of a phase modulator using our prototype photonic chip, scheduled for completion by the end of the third quarter 2009." In June of 2009, it announced its plan to "finish development and build functional prototypes of 40 Gb/s and 100 Gb/s modulators during the first and second quarter of 2010." In May of 2012, it targeted "completion of [Perkinamine Indigo][14] prototype modulator later this year." In March of 2014, Lightwave began "the process of manufacturing its advanced design Silicon Organic Hybrid Transceiver prototype… Delivery of the wafers is expected in early summer."
>
> In March of 2017, then-CEO Tom Zelibor resigned as CEO because "now that the Company has successfully made its commitment to develop an operating prototype modulator," it was time for someone more technical to take over as CEO. In September of 2019, now-CEO Michael Lebby told investors that "work on fully packaged prototypes" of 50Gbaud modulators was still ongoing after first announcing the work on this prototype *16 months earlier* during the 2018 annual shareholder meeting, and despite the fact that Lightwave declared that it had already "developed 50 GHz optical devices based on its existing polymer EO materials" in February and an *official commercial "50 Gbaud polymer modulator offering"* [emphasis ours] in December of 2018. In the same September 2019 letter, Lebby also declared that the "development of 100Gbaud prototypes…is now up and running."
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> **Successful product tests and developments:** In 2013, Lightwave announced "Positive Initial Results from Potential Microelectronics Customer" using its Perkinamine

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[14] This was what it named the chromophores it was then developing.

chromophores. Later in the year it reported the demonstration of “several promising characteristics” in a test by another unidentified company of an unidentified “silicon hybrid device” coated with Perkinamine. At the end of 2016, in “one of the most significant moments in the history of our great company,” Lightwave successfully “achieved high-speed modulation in its first all-organic polymer ridge waveguide intensity modulator prototype.” But the modulator demonstrated merely 5GHz of bandwidth, which was well below the standard optical transceivers being sold by telecom equipment vendors at the time.

In February of 2019, Lightwave announced an “improved thermally stable polymer [that] has more than double the electro-optic response of the Company’s previous materials.” It then presented these results at the European Conference on Communications in September of 2019 (but never published them). In January of 2020, Lightwave craftily changed the story a bit and, instead of a successful test of *polymer materials,* it boasted that it was able to “show data that our ***modulators*** could exceed 80 GHz” (emphasis ours), which is a substantial difference. In October of 2020, it announced that it “optimized a robust, photo-stable organic polymer material for use in the company’s next-generation modulators intended to be trialed with potential customers under NDA.” Two months later it issued a press release for the “exciting breakthrough” of developing a sealant for its future “packaged polymer platform,” which seems less exciting in light of the fact that it hasn’t developed the packaged polymer platform yet.

In August of last year, Lightwave announced another significant improvement in the properties of its polymers, including a *doubling* of the material’s EO effect, “while allowing higher stability during poling and post-poling.” Another interesting feature of the press release was that Lightwave casually referenced its trademarked “Polymer Plus™ and Polymer Slot™ modulators,” though we had a difficult time finding the products anywhere, and the lack of any revenue over the last 7 years would seem to indicate that none of these have been sold commercially. Last September came the announcement that Lightwave’s *chromophores* (i.e., not the polymer and certainly not any actual device) were used in a Polariton modulator that achieved a “world record” 220Gbaud. This was followed by the most recent announcement, in March, that Lightwave’s chromophores were used in another Polariton monitor that demonstrated “enhanced stability.” Details of the speed of this device were very conspicuously absent.

Patent Issuance: Since Michael Lebby became CEO of Lightwave in 2017, the company has habitually made a big deal over patent issuance. We don’t claim to understand all the details of all the patents, but some of them are transparently laughable. About a year ago, for example, Lightwave announced it received a patent for “High-Volume Manufacturing Processes for Electro-Optic Polymer Modulators,” which is curious considering that high-volume manufacturing of EO polymer modulators is currently impossible. In August of last year, the company received a patent on “enhanced optical routing architectures for polymer-based integrated photonics that can be scaled with partner foundries,” which is also curious because no partner foundries

> exist. A recent patent announcement in March "illustrates the design of a monolithic photonic integrated circuit," which is a bit aspirational considering that Lightwave can't even manufacture the underlying material with any consistency, let alone a modulator or an integrated circuit on which the modulator will operate.

Lightwave has regularly made grandiose announcements claiming all sorts of major technological progress, and the unmistakable impression meant to be made by these announcements is that some form of commercial success is imminent (or at least inevitable). Yet in the approximately 15 years in which Lightwave has been a public company, it has generated a grand total of $6 thousand in revenue: None of the innovative prototypes, successful tests, or important patents were ever followed by actual products, or even a mere IP licensing agreement. When the fact pattern is laid out as it is above, the inconsistencies, contradictions, and unfulfilled promises seem to be, at best, a sign of gross incompetence.

How is it possible to boast of work on a modulator prototype, follow that up 6 months later with talk of a commercial product offering, and then tell investors 9 months afterward that work on the prototype is "ongoing?" The company's self-congratulatory product announcements frenetically switch subjects from the chromophores to the polymers to the modulators, and not always in that order. Which is supposed to be the company's core business? And why does the company keep working on successive generations of these products without ever having succeeded in commercializing the prior ones? If the "Polymer Plus™ and Polymer Slot™ modulators" are trademarked, why are there no spec sheets to be found or even mere product descriptions? If Lightwave hasn't even commercialized a polymer material, why is it patenting processes related to foundry-scale chip production?

The industry narrative in which CEO Michael Lebby has framed Lightwave's "opportunity" over the past two years is also strange. In an interview from just a few weeks ago, Lebby responded to a question about "the tech he is working on" by imagining a world in which "the speed of data passing through the internet doubled. What would it mean for us if our bandwidth availability at home tripled, quadrupled, or even was 10X or 100X faster?" Lebby has a long history as an "accomplished technical expert witness" in IP Litigation and has been involved in meaningful research in the field of optoelectronics. Surely he knows that the speed of data passing through the internet has actually *increased by about 10x just in the last decade*! He probably also knows that EO polymers, if they ever worked, have little use in "last mile" applications like "bandwidth availability at home" and would be a lot more relevant to increasing the reach of optical transmission in data centers, wireless backhaul, and transcontinental fiber optic transmission.

Lebby is also fond of trying to simplify complex topics, but in the process he has often distorted the underlying realities. For example, we've seen several interviews, talks, and presentations in which he's compared data transmission to automobile travel. In his story, each bit is a car, wavelength division is the equivalent of adding lanes, high order modulation is like stacking cars on top of each other, and baud rates are the speed limit. Framed that way, who wouldn't want to increase the speed limit? But Lebby is smarter than that, and surely he knows that the speed of light in fiber is the same no matter what the baud rate is. Increasing the speed of the modulator increases the *frequency* of being able to put cars on the road, not the speed of the cars, so actually two cars in different "lanes" would reach their destination at the same time as two cars leaving one after another in a single lane. And actually, putting two cars together one after another in a single lane requires doubling the width of the lane, so it's not that obvious that you gain very much by increasing the frequency of cars on the road. It's true that the cars can travel a bit further that way, but that's a lot more subtle and a lot less groundbreaking.

The contrast between bombastic press releases and seductive narratives on the one hand, and the uninterrupted history of continual failure on the other, is stark. Rather than incompetence, we believe it reflects a systematically promotional corporate management that meticulously tends to Lightwave's public image in the face of an impossible engineering objective.

The "Foundry Deal" and other delusions reflect an investor base that fundamentally misunderstands the optical communications industry

It's possible that Lightwave's years-long stream of optimistic press releases hinting at imminent breakthroughs are aimed at the credulous retail investors that make up the busy InvestorsHub forum on the stock. We almost feel bad for the 638 posters, most of whom have been expressing their enthusiasm and fighting off skeptics for 15 years in over *100,000 posts* on the forum. About a third of that discussion has taken place in just the last year, coinciding with the stock price's rapid ascent.

The most devoted Lightwave investors are *certain* that Lightwave will soon announce some commercialization agreement with a semiconductor foundry. In fact, a major theme of Lebby's recent ASM presentation was Lightwave's supposedly impending "partnerships" with foundries, though the details were scant and the implications ambiguous. For example, Lebby highlighted that Lightwave "has stuff coming back from foundries" by which he seems to have meant assembled modulators, but later in the presentation he admitted that modulator prototypes are still in progress and that a goal for the second half of 2022 was to have "proof of concept prototypes with fabrication from silicon foundries." So what exactly has been coming back from the foundries? We're not sure. Lebby also made multiple references to "foundry partnering" (slide 38), "technology transfer" from Lightwave to foundries (several slides), and "expecting results from the foundries" (slide 35) in the next 12 months. But what kinds of results to expect or what the nature of the partnering would look like was mostly vague.

The only tangible example of "technology transfer" or "partnering" that Lebby referenced was the future adoption of polymers in the PDKs (process design kits) of one or more foundries. The message board excitement over PDKs (and Lebby's intentional focus on the matter) suggests that Lightwave's investors don't really understand the concept in the first place. A PDK is just a library of basic components, along with their parameters, that's used by engineers to design and model chips before manufacturing. Lightwave may yet be able to cajole its way into a foundry's photonic PDKs – in fact Lightwave may even build its own PDK and transfer it to a foundry – but that's a completely hollow achievement if there's no end-user. Lightwave would need to find a transceiver manufacturer that actually wants to design a polymer modulator into its chips.

That aspect of the optical communications industry (and chip manufacturing in general) seems to be completely lost upon the Lightwave devotees anticipating future partnerships. For Lightwave to sell its chromophores or its polymer, it would need to find a company to design and manufacture a modulator using those materials, and not in a mere one-off experiment like Polariton. If Lightwave were to design its own modulators that would seamlessly integrate into a silicon chip (as Lebby claimed at the ASM), it would need to license those designs to the device manufacturers that sell transceivers. Either way, foundries don't manufacture modulators or photonic chips "on spec." Rather, they respond to orders from device manufacturers that are designing and selling optical modules and transceivers (e.g., Acacia, Ciena, Infinera, Marvell, etc.) In order for Lightwave to commercialize its products or generate any revenue, *these end-customers would have to design their chips with polymer modulators in the first place*. None of these companies are going to waste engineering resources to design a device using a PDK for a polymer modulator without both rigorous testing and *the demonstrable existence of a repeatable and consistent polymer fabrication process*. Of course, that doesn't exist, so all of this is just a pipe dream.[15]

Obsessive Lightwave investors, many of which have posted *thousands* of times, have also been repeating the same "faster" and "lower power" mantras mindlessly for so many years without understanding that they're both untrue and irrelevant. Perusing through years of messages, speculation by these shareholders about an imminent buyout has been discussed hundreds of times. Some of them even claim that they were part of the original founders of Lightwave and own millions of shares. We have no idea if that's true, but we think they're going to be very disappointed with how things proceed at Lightwave.

The fact that so many of the most basic underpinnings of optical devices and the optical communications industry completely elude the retail shareholders is perfectly representative of their delusional overconfidence. It's not surprising that accusations of "naked shorting" and "dark pool" trading abound, while almost every mention of polymer competitors like NLM or polymer device hopefuls like Polariton reveals a fundamental misunderstanding of what any of these companies do, and the stage of progress at which they stand. The perverse combination of complete ignorance and intense loyalty is bound to end badly.

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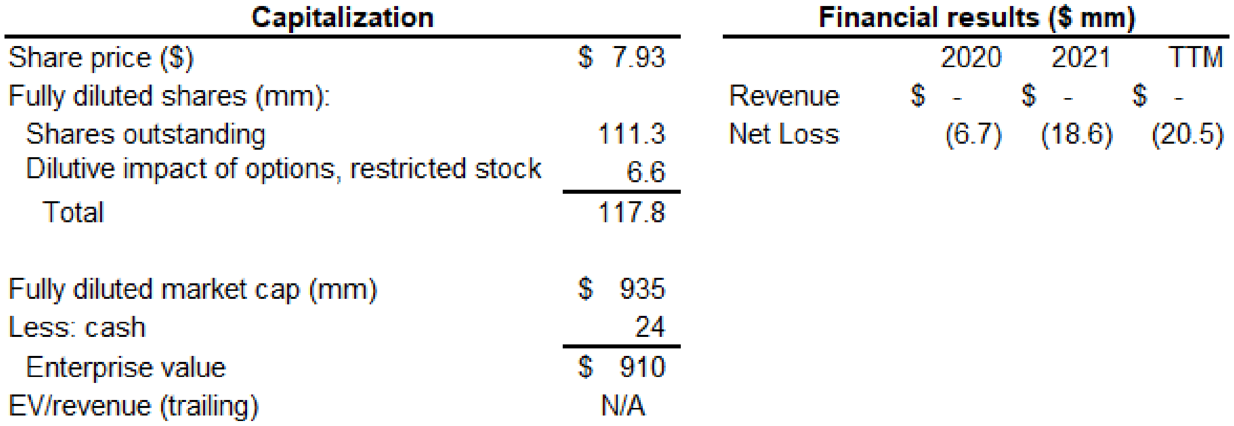
[15] Even if it did exist, as we discussed previously, the bar for tinkering with polymers in high-volume foundries would be extremely high just because the potential gains to be made from increasing baud rates at this point are complex and limited given the spectral limits of legacy installed fiber and equipment.

IV. Conclusion

Lightwave Logic: Capitalization and Financial Results



Capitalization	
Share price ($)	$ 7.93
Fully diluted shares (mm):	
Shares outstanding	111.3
Dilutive impact of options, restricted stock	6.6
Total	117.8
Fully diluted market cap (mm)	$ 935
Less: cash	24
Enterprise value	$ 910
EV/revenue (trailing)	N/A

Financial results ($ mm)	2020	2021	TTM
Revenue	$ -	$ -	$ -
Net Loss	(6.7)	(18.6)	(20.5)

Source: LWLG company filings, Kerrisdale Analysis

Underneath the veneer of advanced technology at Lightwave Logic, there is almost nothing. The company has never *verifiably* produced any polymer, let alone a device, that improved the speed or power consumption of optical communications. The only thing it has ever produced to be verified by a third party is a batch of chromophores that were used by a *different company* to fabricate materials that would go into a modulator that ended up transmitting at impressive speeds over a grand total of 100 meters.

As for the speed and power claims made by Lightwave with respect to devices it claims to have constructed, they aren't even that impressive. The speeds enabled are lower than those of mass-produced commercially available optical devices, and the power claims are laughable given that they don't address the DSP functionality that is the defining feature of modern optical devices. What's worse is that assuming Lightwave's claimed devices exist, it's pretty clear that they are one-off creations because the company lacks the capability to manufacture an EO polymer with any consistency or acceptable yield. That's not necessarily Lightwave's fault. After all, this knowledge has been sought in the research community for almost 40 years to no avail.

But the implication is that Lightwave has no chance of commercializing *anything* in the foreseeable future. Not a polymer, not a modulator, and certainly not the kind of miniaturized optical module that has taken a decade for large teams of talented engineers to perfect at companies like Acacia and Ciena. We think it's highly unlikely (probably impossible) for any of that to be achieved by a company with merely 19 employees whose CEO works (and frequently moonlights as an expert witness) 1200 miles away from corporate headquarters, even if the technology worked. As it stands, even if the technology *did* work, it's fairly clear it would only be relevant in a narrow range of niche applications because increasing baud rates at the expense of total spectral efficiency would result in a net *reduction* of fiber optic communications capacity in most use cases.

Lightwave will undoubtedly continue its high frequency of promotional announcements – impressive-sounding product tests, more prototypes right around the corner, unnecessary patents with meaningless technological jargon, and maybe even a PDK – all to try and impress a fan base of naïve shareholders. But what shareholders are expecting amounts to a miracle, and when it doesn't happen – and it won't – the path back to microcap status could be faster than the speed of light.

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