The First 147 Years of OptoElectronics

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Abstract
Photonics deals with the practical generation, manipulation, analysis, transmission and reception of photons. The Photonic Computer is not yet here, but we use the photon for countless other tasks. We have been harnessing the photon for thousands of years to predict changes in the seasons and to achieve many other results in astronomy - the oldest science. Photonics moved ahead when optoelectronics (OE) was added as a new subset in the 19^{th} century. The earliest OE experiments were in display technology, still a major sector today. Optoelectronics also became part of the telecommunications revolution first launched in the late 1800's. A beam of modulated sunlight was decoded into sound using a selenium photoelectric receiver for the FIRST wireless and the first OE telecom component (Figure 4). The wireless Photophone confirmed the value of photons as messengers, but we would wait for nearly a century for breakthroughs to make the concept practical. Finally, the laser was developed that would make OE telecommunications viable. Today, Optoelectronics technology lets us send mail around the globe in a split-second, surf the incredible Internet, and transact all kinds of business using electrons and photons.

This paper will highlight significant OE events including the development of display technology, optical fiber, and the deployment of photonics-based telephone systems that preceded the Internet. A comparison of solid-state electronics with OE will show that both industries use fundamentally similar principles for devices. One major difference has been the choice of chemical elements for each domain. While electronics became based around silicon, OE selected almost half of the periodic table to produce a myriad of complex structures that deliver the desired photoelectric effects. Thus, the fundamental difference is *elemental*.

The last sections will deal with newer OE technologies, including VCSELS, MEMS-based aligners and MOEMS switches. We'll conclude by examining the challenges ahead for OE and the chances of pursuing the same strategy that made electronics the most successful and largest industry in the world. True success for OE is still in the future.

Photonic Displays
The pioneers in electronics were fascinated by the light generation phenomenon produced by the application of high voltages to vacuum enclosures. In the mid-1800's, experimenters built glass tubes fitted with electrodes. Unusual discharge phenomena resulted when air was removed from these tubes. Thus, the hermetic package was born. Geissler tubes (Figure 1) produced colors when high voltage was applied. Phosphors were next added to convert the invisible electron beams to light. When a cross-shaped metal shield was placed in the path of the beam, that image was projected on the screen (Figure 2). We now had an OE display device and the cathode ray tube (CRT) was almost here. Before the turn of the century, Braun perfected a scanning CRT that used electrodes perpendicular to the electron beam to control it (Figure 3). So before we had reached the 19^{th} century, optoelectronics display devices were well along.

Fig.1 – Geissler Tube 1857

Fig.2 – Crookes Tube

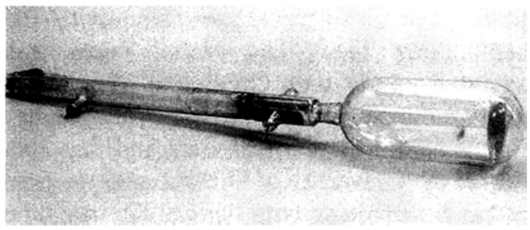


Fig.3 – Braun Tube 1897

The Braun Tube evolved into the modern display device used for television and monitors. The same basic principle has been used for over 100 years. But today, newer flat panel displays attempt to dethrone the CRT and this will certainly happen. Perhaps the organic light emitting diode (OLED) will win and supercede the mature glass & metal OE product.

Telecom Photonics
During the same period, telephone pioneer Alexander Graham Bell was experimenting with light as a means of telecommunications. Although his telephone system was enjoying huge success, Bell was troubled that communications was handicapped by the need for wires making it impractical for ships. He attacked the problem by

abandoning copper wire and moving to photons. He used an opto-mechanical mechanism for the transmitter that relied on sunlight as the photon source. A microphone vibrated a mirror to modulate the sunbeam. But the light source was inadequate and nothing suitable would come along for 80 years. Perhaps appropriately, one of the facilities that helped pioneer the needed light source, the laser, was AT&T's Bell Labs. Figure 4 shows Bell's Photophone communications receiver.

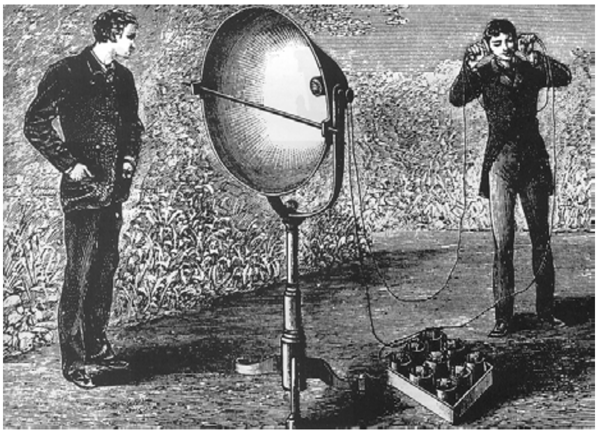


Figure 4 – Photophone Receiver

A large number of laser types were developed after the first gas laser in 1960 (Hughes). The diode laser would come 2 years later and this class had the right characteristics for telecom. The first diode lasers had an unusable short lifetime, but within a year the products were good enough for commercial use. The diode laser has become the workhorse of modern terrestrial long-distance communications.

The Glass Highway

Although the laser source was now available, the earth's atmosphere was not a suitable medium for long distance. Photonics needed a conduit material that would be analogous to the copper wire of electronics. Some form of glass seemed obvious. Glass was known for at least 4500 years in Egypt and Mesopotamia. Glass fiber has been dated back to 1600 BC. Europeans even spun glass fiber in the 18th century, but clothing of glass had more appeal than applications in telecom.

In 1881, William Wheeler received US patent 247,229 for a method of illuminating a residence using light piping, but still not much thought was given to long-distance transmission. Progress was finally made in the 1950's when a flurry of activities and discoveries occurred in the glass fiber field. Researchers in Denmark, the USA and Europe, moved ahead on longer-range optical fiber, as *total internal reflectance* became better understood. The concepts of graded index fiber and outer cladding were gaining support and providing results. But photonic image transmission was still encumbered by direct image fiber bundle methods rather than coded signal concepts that would be needed. We had not embraced digital thinking.

In the 1960's, work progressed on single fiber links and the laser was now an inseparable part of the technology. The gas laser (1960) was soon followed by the diode laser in 1962, and this would be the transmitter source of choice, then and now. Finally in the 1970's, fiber development progressed rapidly at Corning, Bell Labs and English research establishments. Bell Labs ran tests at Norcross, GA in 1976 using graded index fiber at 45mB/second, but short laser diode life was a problem. But by 1977, AT&T, ITT and the British Post Office all had fiberoptic communications up and running. And by the 1980's, commercial fiberoptic links were established between major cities to handle telephone traffic. Multiple wavelengths were starting to be deployed and optical submarine cable connected France and England.

Fiberoptic telecommunications was on its way. Telephone service was greatly improved and "you could hear a pin drop". Costs had come down and transatlantic telephone calls were a reality for almost anyone. But the Internet, a truly disruptive technology, would be the Big Event. The Internet placed massive demands on the telecom systems and coined terms like, "insatiable bandwidth". Since optical communication had already been proven by the telephone industry, the Internet embraced it fully. The need for much more capacity propelled OE into a new orbit with a much more dynamic model. The business spotlight was now shining on OE and everyone wanted to jump on that "bandwagon". But wrong decisions in both business and technology caused the wagon to lose some wheels in 2001. Some are waiting for the wheels to be put back on and hope that the wagon moves forward again by 2003. Others want to see better wheels. Yet others, a minority, want to see the entire optoelectronics vehicle redesigned into one with the stability and durability to travel to a bright future. Let's look more closely to understand why we failed and how to succeed.

The OE Device – Can it be Integrated?

When you look at electronics, the amazing success is mostly due to high-level integration. A single computer chip now has 180 million transistors (IBM Blue Gene). What do we have in optoelectronics? A laser with a lens is heralded as breakthrough integration. Since OE is at least as old as electronics, why is there so little progress?

Let's first look at the laser diode shown in Figure 5 along with a Vertical Cavity Surface Emitting Laser (VCSEL) and an electronic type. All are semiconductor solid-state devices that are closely related. All three have PN junctions, but materials are very different. The light emitters are designed to maximize light output. The electronic diode also generates some light, but this is an unused byproduct. The electronic diode can be made from doped silicon. OE emitters and receptors are much more complex and are generally designed around a III/V element combination; junctions made from a Group III and a Group V chemical element. The most common emitter chemistry is gallium (Group III) and arsenic (Group V) formed into gallium arsenide (GaAs). But many other elements are added that include phosphorus, indium, aluminum and others. Table 1 lists elements used in Optoelectronic devices.

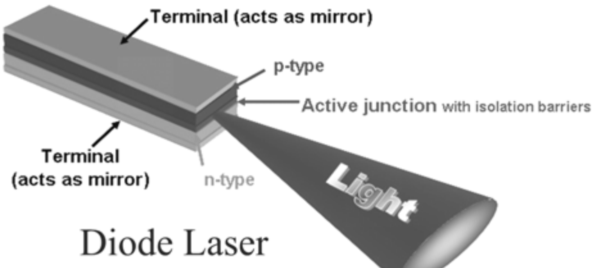


Figure 5A – Laser Diode

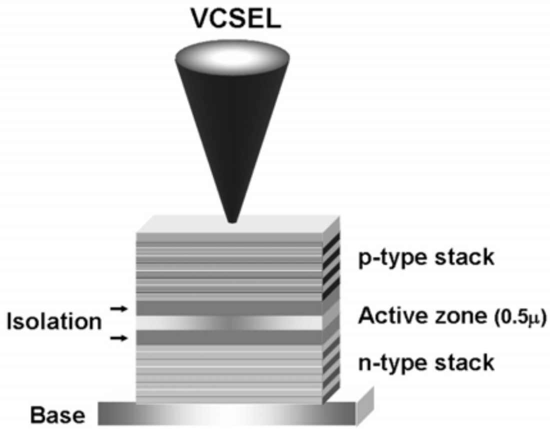


Figure 5B – VCSEL

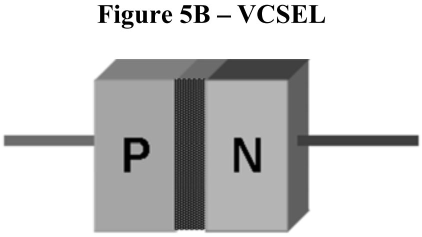


Figure 5C – Electronic Diode

Now back to the question of OE integration. The first problem is the much more complex device chemistry. While electronics uses a trace of Group III and V elements, optoelectronics builds structures with these elements and compounds. But dozens of other elements are also used. Some of the elements and compounds for different devices are not compatible. Even if that problem is overcome, the manufacturing process will be more complex than for electronics. There is still a larger issue. While electrons obediently follow copper or aluminum conductors left, right, up or down, photons cannot make right-angle turns in waveguides. The light simply leaks out if the critical minimum radius rule is violated. The optical IC will need some form of integrated prism or mirror at each turn. While this is not impossible, there is not yet a practical approach for achieving sharp optical turns at the micro-level.

Table 1 – OE Chemical Elements

Gallium (Ga)
Arsenic (As)
Indium (In)
Phosphorus (P)
Aluminum (Al)
Oxygen (O)
Yttrium (Y)
Erbium (Er)
Magnesium (Mg)
Fluorine (F)
Lead (Pb)
Gold (Au)
Platinum (Pt) Palladium (Pd)
Germanium (Ge)
Iron (Fe)
Chromium (Cr)
Rubidium (Rb)
Lithium (Li)
Niobium (Nb)
Praseodymium (Pr)
Titanium (Ti)
Nickel (Ni)
Nitrogen (N)

Another problem is the basic behavior of photons compared to electrons. The dominant wave properties of the photon compared to the particle-like electron make storage unlikely at chip level. Yes, light has recently been slowed and stopped in the laboratory, but we are not close to a simple on-chip storage mechanism. This means that the OIC will not have the equivalent of the capacitor that is so vital to electronic computer and memory chips. All of these many differences make the OIC a very significant challenge. But is there really a commensurable reward for developing the OIC? Lack of a favorable return on the large investment needed for the OIC could mean that it's "light years" away.

The Packaging Predicament

The hermetic package was invented around 1855 for the early photonic display tubes. The same concept is used for today's OE devices. Unfortunately, the hermetic package is still very costly and assembly is not easily automated. OE packaging can account for 80 – 90% of component cost compared to only 4 – 5% for electronics. Although the optical IC may not be close, the high OE package cost can be attacked now and we should not wait.

We may note that electronics quickly dropped package cost early by moving to plastic molding and automation. Today, electronics is reaching for the final frontier, wafer-level packaging (WLP). Can we use any of the electronics packaging strategies and technologies for OE? Plastic has been vetoed by the OE industry from the beginning and the default position has been to use the full hermetic metal package. But while the metal hermetic may protect the OE device, it may be helping to degrade this cost-burdened industry. Certain plastics, like Liquid Crystal Polymers (LCP), have barrier properties that are an order of magnitude better than epoxy molding compounds. They must be considered for OE.

Can the NHP work for OE?

The near-hermetic package (NHP) is a hybrid cross between the low-cost non-hermetic plastic molded package and the expensive full hermetic. The idea is to retain the lower cost of plastic packaging while boosting hermeticity to an acceptable level. One starting point can be the selection of a practical polymer with the highest barrier properties. Many consider LCP to be the best choice especially since this type can be injection molded and the moisture barrier performance is equal to that of glass. Several companies, including Silicon Bandwidth and Cookson Electronics have focused on the LCPs. Table 2 gives properties for commercial LCP.

Table 2 – LCP Properties

MATERIAL PROPERTIES	value
Dielectric Constant Dk	< 3.0
Dissipation Factor	0.003
Water Absorption (%)	0.1
Liquid Crystal Transition Temperature (Celsius)	335
Solder Heat Resistance (Celsius)	280
Warpage @ 200C (%)	1
Coefficient of Thermal Expansion CTE (ppm/C)	16
Coefficient of Hygroscopic Expansion (ppm/%)	2
Accuracy of Thickness (%)	5
Peel Strength for Copper Foil (kgf/cm)	0.8
Chemical Resistance	Excellent

Package designs are under development and in testing for OE products that require an external light path such as miniature displays, detectors and MOEMS projector chips. These require a glass lid, or “skylight”. Several glass lid-sealing methods have been explored and a laser welding technique is one of several showing promise. Our approach at Cookson is to seal glass to LCP cavities with our NIR (860 nm) laser. The beam travels through the glass to melt and fuse the plastic. The process can be run in vacuum or inert gas atmospheres. Getters can also be used inside the package for added reliability. We are also moving to wafer-level sealing of glass-to-wafer using LCP preforms. The concept is shown in Figure 6.

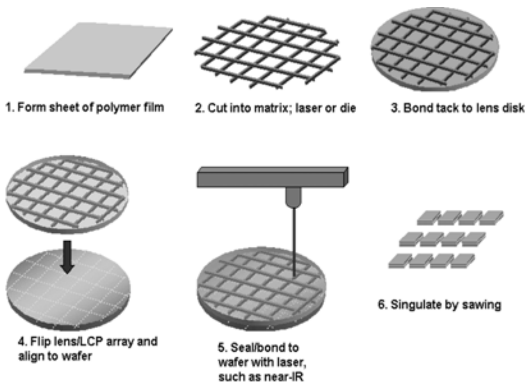
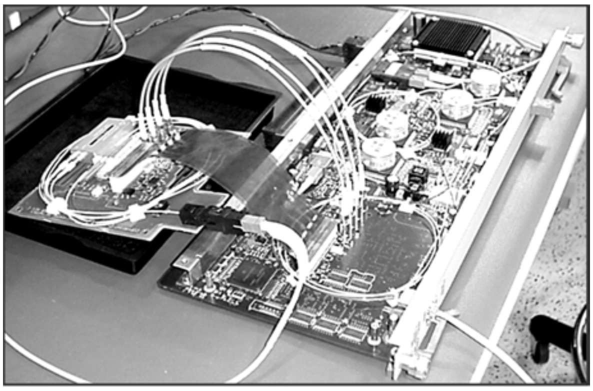


Figure 6 - WLP Laser Process

OE Circuitry Chaos

Today’s optical board assembly uses some of the most difficult processes ever contrived and most were never intended for efficient automation. Fiber fusion is at the top of the mountain of difficulties that’s climbed every day. The steps of preparation, alignment, fusion and protection take too many minutes and the cost is about 10,000 times more than for the electronics connection since there is no equivalent to soldering. Although the equipment automation industry has accomplished tremendous feats, the best machines still require minutes per connection compared to 10 to 20 joints in just one second for electronics. If we were to build an electronic laptop with today’s optoelectronics semi-automated assembly of discrete devices in hermetic packages, this product would soon vanish. That laptop would be bigger than a house, weigh many tons, and cost millions of dollars. Who would buy it? Maybe there really is a problem with OE technology and we should stop blaming earlier business strategies.

Is there a better way of transporting photons? Some suggest that short-range free path is the right approach. This eliminates pigtails and fiber fusion at board level. How would it work? The devices would be packaged so that a photonic link is made to the board, perhaps with a VCSEL in flip chip format. The PWB would need light ports and waveguides, but this would be a passive system. Figure 7A shows today’s board while Figure 9 shows the embedded waveguide/surface link concept that is being developed by companies, universities and government laboratories in the US, Europe and Asia.



Picture is representative of products built by Celestica.

Figure 7 - Opto Board Today

The Ideal OE Telecom Technology and System?
What would the Optoelectronics industry look like in the future if we superimposed the successful and relevant attributes of electronics? First, there would be some level of device integration. We would want to integrate features to give us a single-chip optical transceiver – the most fundamental component for telecommunications. Although this device would still have low-level integration as viewed by the electronics world, the challenge would be significant for OE. But the payoff is the generation of a multi-million-unit/year consumer market. The transceiver chip could drop cost by 1 to 2 orders of magnitude and open up vast new markets. We would also like to have an amplifier IC to replace the erbium doped fiber amplifier (EDFA) with its coils of fiber and countless hand-assembled components. Innovation is needed to produce the equivalent of the fiber coils in chip, but modern computer chips have the equivalent of hundreds of meters of metal wire. The in-chip coils would need a mechanism for overcoming the minimum radius problem, but there are solutions in optics that can be reduced to reality with physics and chemistry.

Next, we want to shed the "butterfly", the costly package that keeps optoelectronics from flying. NHP is the choice. Work now in progress at leading companies, universities and government laboratories will surely bring success, especially if the main hurtle is old attitudes. And perhaps OE devices will reduce packaging requirements with in-chip passivation, the successful approach from electronics. The passivated OE chip will tolerate a higher level of active gases and moisture. Perhaps the combination of chip passivation and the low-cost NHP is the way to go.

But what about the fiber connections that we can't avoid, can we get help from MEMS? Several MEMS fiber aligners have been developed and at least one is close to commercialization. A MEMS auto-aligner could be placed in the package to align the fiber to chip, or to align the optical bench to an incoming fiber. The device could always be active or used initially and for periodic tuning. Figure 8 shows a MEMS aligner from Boeing.

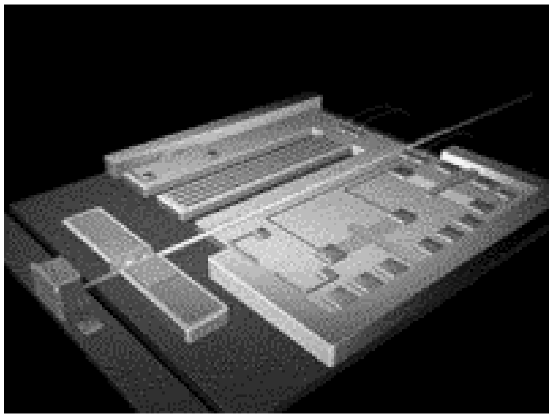


Figure 8 – MEMS Optical Aligner

What about board assembly often referred to as level-2? Would we still want to hand solder non-SMT packages and fuse fiber? Of course not! We could move to the free-path chip-to-board scheme. The opto-board would have embedded waveguides. We already have a good start on 2-dimensional waveguides and many types have been built. The challenge is to add the 3rd dimension, the Z-axis, that may require the equivalent of mirrors or prisms. But this is the same problem faced for chip integration. We will need to make right angle turns or design fiber that can make a tight radius, a concept that 3M Co. is pursuing. Figure 9 shows the waveguide embedded board concept. It's also worth mentioning that some are working on plug-in OE components that will use optical "rods" and perhaps look a little like pin grid arrays.

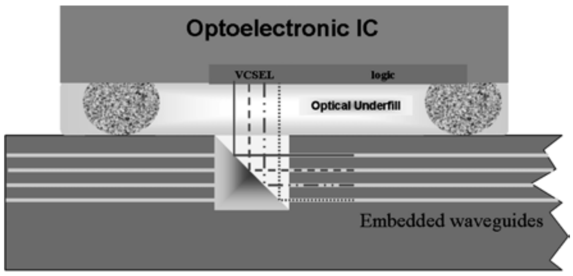


Figure 9 – Opto Board with Embedded Waveguides

Photons to the Home
What will future consumer connectivity be like? The last link, the "speed bump" bottleneck to the end user will be broken. Today's Internet is like a 10,000 lane super-highway, but the path to your home is a *little dirt farm road*. Your road will finally be paved so that "photons-to-the-home" can travel freely. Perhaps we will use optical fiber if we wring out hardware cost and make it reasonable. Perhaps the photons will travel through space as "light" or radio waves. Broadband wireless is after

the home market once it conquers high-density public areas like airports. But Bell's old idea of data-over-light could be an answer. Light poles could have optical transceivers that communicated with a transceiver through your window. This principle is now used for building-to-building links in cities, so why not the shorter distance to the home and office? Figure 10 shows a modern free-space transmitter along with the Bell Photophone. The principles are the same and the time gap is 122 years. Should we look back to the future?

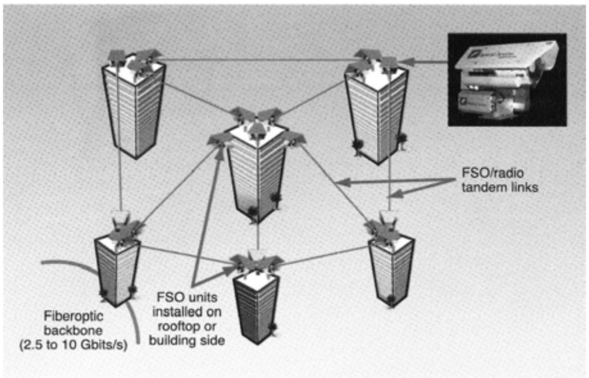
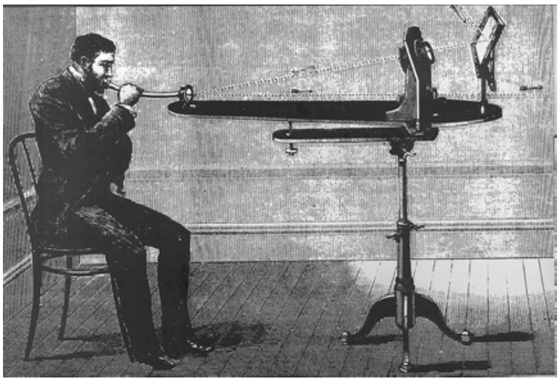


Figure 10A – Building to building

Figure 10B – Modern Photo-Data-Phone



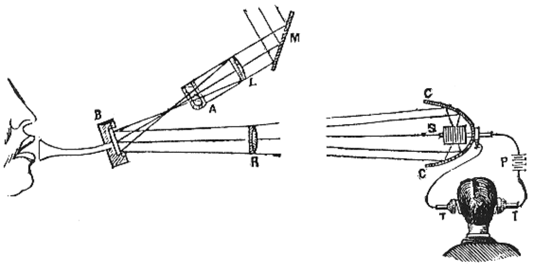


Figure 10C – Bell's 1880 PhotoPhone