OPTOELECTRONICS – ADDING A LITTLE LIGHT TO THE NANO-WORLD

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ABSTRACT
Optoelectronics (OE) is perhaps older than electronics since it began in the late 1800's with the wireless Photophone that could transmit voice to ships. Over a century later, OE has been propelled to center stage as the core technology of the Internet. The modern Internet uses optoelectronics almost exclusively for long-haul links over continents and under the oceans to provide maximum bandwidth and reliability. This paper will describe basic OE devices, such as optical transmitters, and more complex integrated systems such as MOEMS (Micro-electro-mechanical Systems) switching devices. Electronics and photonics will be compared for similarities and differences at several levels. OE issues, especially those of assembly, will be discussed and basic optical fiber connection methods will be covered. OE is rapidly becoming a vital component of EMS business, but this is not a technology for the timid or the risk avoiders.

INTRODUCTION
Optoelectronics almost certainly began when Alexander Graham Bell developed the Photophone in 1880. The transmitter used natural sunlight because there were no suitable artificial sources at that time. Sound vibrated a mirror to modulate a sunbeam. One can argue that this was really an opto-electrical device without real electronics. However, the receiver used the photoelectric effect that had recently come to the attention of inventors like Bell. The element selenium had special properties that would prove invaluable for optoelectronics. The conductivity of selenium films was proportional to the intensity of light directed onto its surface. Bell reasoned correctly that selenium could be used for his Photophone receiver. Voice modulated light should produce voice if an earpiece was connected to the selenium photocell. Bell was right; his voice-on-a-sunbeam could be heard at the receiver prompting him to say, "I have heard a sunbeam sing…". Figure 1 shows the Photophone.

But the Photophone, Bell's greatest invention according to the man himself, would not be practical without major breakthroughs in light-producing devices. The electric light bulb would not suffice since its glowing filament had a very slow response time. The laser, developed at Bell Laboratories in New Jersey, would become the key to optoelectronic voice for photonics communications. Today, the laser diode is the transmitter for both fiberoptic and free-space (fiberless optics) transmissions.

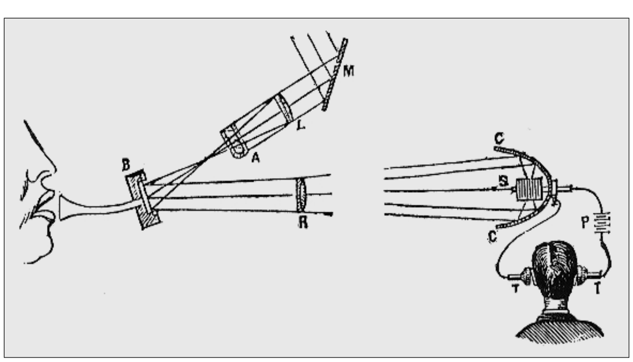

Figure 1A –Photophone Principle

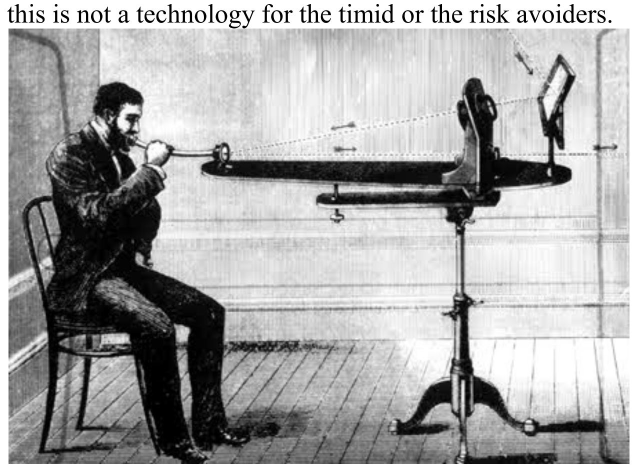

Figure 1B –Photophone Transmitter

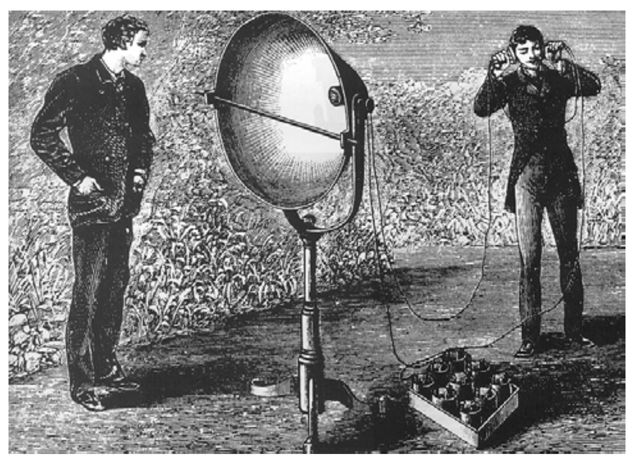

Figure 1C –Photophone Receiver (all from Bell Labs)

OE SOURCES & TRANSMITTERS
Several types of lasers are used as sources. The laser must be capable of rapid modulation while maintaining extreme stability. Power output is less important as lower loss fibers are developed and amplifiers become more efficient. Even the relatively low power VCSELs (Vertical Cavity Surface Emitting Laser) are starting to be used for short-length MAN (Metropolitan Area Networks). The laser is typically configured into a module with the appropriate supporting electronics and

fiber connections. The most common package is a metal hermetic enclosure with protruding electrical wires and one or more optical fibers. The fiber is sealed into the metal package using special solder alloys. The fiber end must be metallized to make it solderable. Figure 2 shows an OE laser source before the package is sealed while Figure 3 shows a high-speed Internet transmitter.

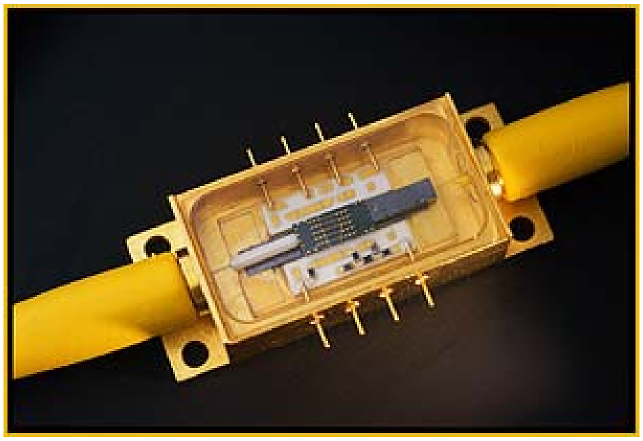

Figure 2 – OE Laser Module – Nanovision

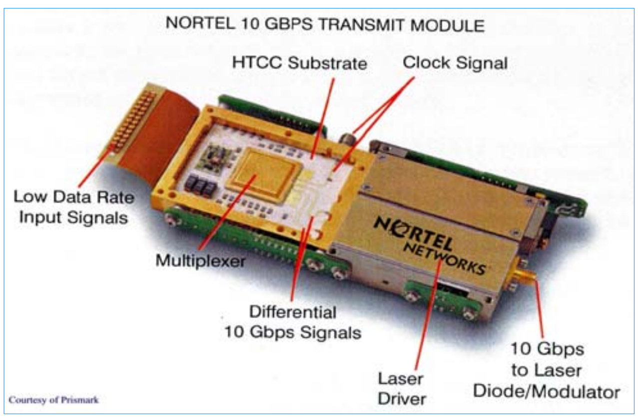

Figure 3 – Laser Transmitter– Nortel Networks

OPTOELECTRONIC RECEIVERS

Receivers detect modulated light (more commonly infrared) and convert it to electrical impulses. In a way, the OE receiver uses the same principle as the 1880 Photophone receiver. Figure 4 shows a 10 GB OE receiver.

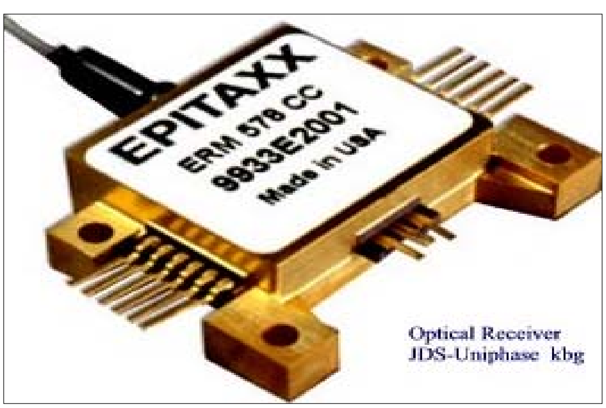

Figure 4 – Internet Receiver – JDS-Uniphase

OPTICAL FIBER

The "wire" of OE is glass, a great electrical insulator. Photonic signals are conducted along the inside of glass fiber that is only about 9-microns in diameter. That small diameter is somewhat fixed by the laws of optics. The small diameter insures that light remains trapped inside by total internal reflectance. There is one exception. If the fiber is bent beyond a critical radius, the photons will not make the curve and will escape. Unlike copper wire, photonic wire cannot be bent into right angles even if the glass would not break.

OPTICICAL CONNECTIONS

Here's where the great differences between OE and electronic assembly start showing up – making connections. We have grown up in the electronic world of solder connections and take the wonderful joining material for granted. But think of where SMT assembly would be if solder had not yet been invented. How would you connect package leads to the PWB? Probably by welding. Now think about welding each and every joint – one at a time. The level of difficulty would increase by orders of magnitude and so would the cost.

Now enter the optoelectronics assembly universe. This is an alien world without optical solder. Sure, we still have metallurgical solder and use it for fixing and sealing optical fibers, but there is no viable optical solder. This means that joints are made one-at-a-time by fusing the conductors together. There is no self-alignment that solves so many problems in SMT. But also recall that fiber is only about 9-microns in diameter. One of the major problems in OE is thus the connection process that involves fusing tiny glass strands together. The process can take minutes and cost many dollars per connection.

An electric arc is a common source of fusion heat but lasers can also be used. Most of today's assembly is still manual and requires very skilled workers. However, automatic equipment has become available from several companies. The best results are obtained by active alignment where light intensity is optimized as the robot moves and sometimes rotates the fiber. Even with automated equipment, the fiber fusion process is slow and costly. While "optical solder" would be a major breakthrough many optical experts do not feel that it will happen.

The fusion process has several steps. First the fiber ends must be very clean. Even a 1-micron particle will mean trouble. Next, the fiber must be cleaved with a diamond tool at a near-perpendicular angle. The fibers are brought together and a plasma flash cleans the ends just before full power is applied to melt the fiber. But before the fusion step, several minutes of alignment time may be required even with the best machines. The splice must be protected with a coating or a shrink fit splint. Even with all of these precise steps, there will still be some small loss. While connectors can be used, they add a higher insertion loss. Figure 5 shows a board with OE devices and fiber connections. Figure 6 shows an automatic optical aligner.

Figure 5 - Celestica OE Board

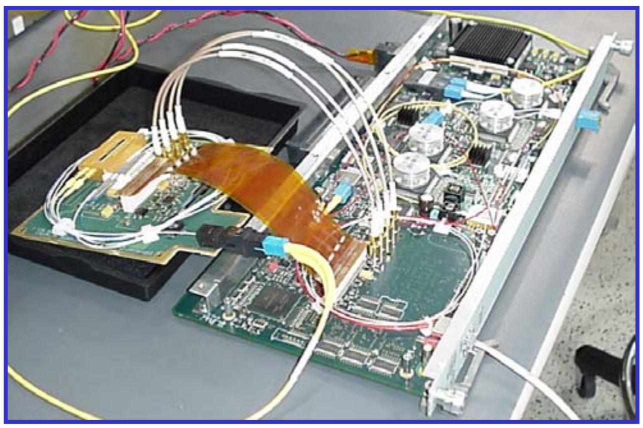

Figure 6 - Automatic Fiber Aligner

AMPLIFIERS

Optical amplifiers must be added along the way to boost signal strength even with the best low-loss fiber. Several types exist, but the most common for the Internet long haul is the Erbium Doped Fiber Amplifier (EDFA). This is a pure optical system where the amplifying energy is light. The erbium atoms within the length of amplifier fiber are energized to an unstable excited state with a pump laser and are triggered by the signal photons causing them to emit the identical wavelengths as they drop back to a stable state. The pump wavelength can be 980 or 1480 nanometers (nm). Raman amplifiers are also available and offer more power but are more complex.

ATTENUATORS AND OTHER OE DEVICES

There are many more OE devices that are needed to carry signals along the Internet since much more is happening than photonic signals just zipping through fiber. While the speed of light is a constant in a vacuum, velocity is wavelength-dependent in glass and other media. Amplifiers are not perfectly linear and so various compensation devices must be used. Attenuators reduce wavelengths that are too intense. However, equalizers can be used that measure and adjust the spectrum and provide automatic compensation. Light can also rotate and this requires compensation. Limits of scope of this paper make it sufficient to say that many other OE devices are used.

SWITCHES AND ROUTERS

As with the telephone system, the Internet signals must be sent to the proper addresses. Data packets are attached to e-mail and web-based information that tells routers where to direct the blocks of data. In fact, your e-mail may be broken up into several packets that can take different routes but eventually join up in a seamless manner to get the message to you. Today, nearly all the Internet routers are electronic. This means that photonic data must be converted back to electrons using an OE receiver. Once routed in the right direction, the electrons are converted back to photons so that the message can travel through fiber. This represents a double conversion. A signal moving across the world may encounter more than a dozen conversions. While this system works, it becomes increasingly awkward and inefficient as more data is coded into more wavelengths to boost bandwidth. Before discussing optical switch solutions, let's look at Internet architecture and multiplexing.

INTERNET STRUCTURE

The Internet consists of a long haul or fiberoptic backbone that spans continents and the entire globe. Subterranean and submarine fiber cables literally span the entire earth. An incredible glass super-highway that carriers phone, data, e-mail and web pages, connects us. Cities and large metro areas contain loops of fiber that tie into the backbone and then distribute links to smaller rings. Figure 7 shows this configuration.

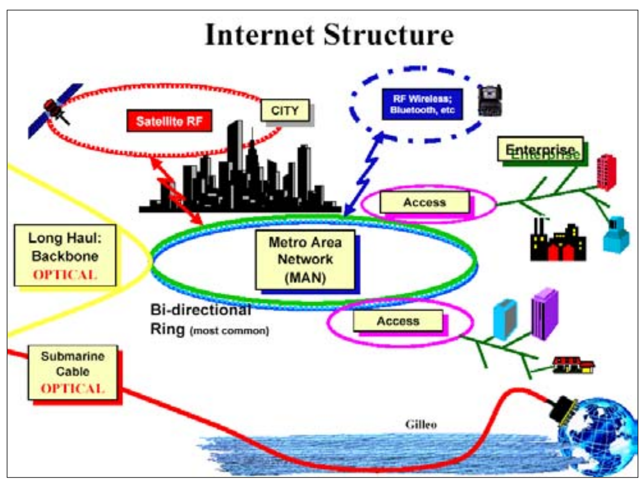

Figure 7 – The Internet (by author)

BANDWIDTH BOOST

The bandwidth capability of OE is over a million times greater than for copper-based transmissions. The first boost comes because of frequency. Photonics frequencies are about 1-million times higher than radio, even Bluetooth. Since bandwidth, or data per time unit, is directly proportional to frequency, OE starts with a big lead. And if this wasn't enough, optical multiplexing works exceedingly well. Photons are weightless and chargeless making interactions minor. This allows many wavelengths to travel over the same fiber independently. The common method of OE multiplexing is called WDM for wave division multiplexing. Each data stream uses a different wavelength or "color". The wavelengths, called lambda, are multiplexed together into one data-rich stream that travels over one fiber. Today, the number of lambda is about 100 and gives a 100-times bandwidth boost. Since the higher frequency already yielded a 1-million multiplier, the result is a 100- million boost. This is under theoretically perfect conditions and the practical number may be less, but is certainly very high. But since the realistic number of lambda is closer to 1000, 1-billion boost may someday be realized. Figure 8 shows the multiplex/demultiplex scheme.

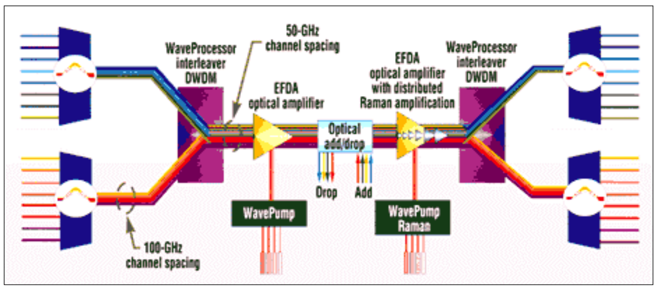

Figure 8 – WDM – Photonics 2001

Now that the background on the Internet structure has been reviewed, let's go back to the data routing problem. How can we avoid the double conversion from photons to electrons and back again? We obviously need a photonic switch. There are optoelectronic switches that could be used today. But we need to add one more technology at this stage of development and that is mechanics. The all-optical switch employs micro-mechanical light-directing elements that can route photonic data beams. The addition of mechanics to electronics brings us into the realm of MEMS, Micro-Electro-Mechanical Systems. Adding optics gives us Optical MEMS or MOEMS - Micro-Opto-Electro-Mechanical Systems. The next section describes this fantastic technology.

MEMS & MOEMS

Microelectromechanical Systems (MEMS) have been with us for a few decades. The first patent was filed in 1952. MEMS products save thousands of lives each year. The air bag electronics system contains a MEMS accelerometer that constantly measures changes in vehicle velocity. Rapid deceleration is interpreted as a crash that causes the MEMS device to send the deployment signal. The MEMS reaction is so swift that the airbag is in place before a driver could strike an injurious surface. The sensor chip is an electromechanical system made of silicon. Suspended micro-beams move position during changes in motion. The circuit is designed as a variable capacitor and beam (capacitor plate) movement produces electrical output. The electronic circuit is integrated into the same silicon platform that contains the mechanical sensor and we can refer to this as intelligent MEMS.

While the accelerometer may seem like a simple and trivial device, many technical problems were solved for success. First, the processes of fabricating 3-dimensional moving parts needed to be developed. Many government (especially Sandia in the USA), university and industrial groups worked on fabrication and this effort is expanding today. We now have several fabrication processes for MEMS including some that can be run in existing semiconductor foundries. The tiny mechanical parts, with their very high area-to-mass ratio, experience all kinds of problems not seen in the macro-world. Small parts can easily stick together and this phenomenon is called, "stiction". Micro-friction and stiction can make a device unworkable or unreliable. These problems are only partially solved and these are fruitful areas for research.

Adding Light to MEMS - MOEMS

The technology is called MOEMS – Micro-Opto-Electro-Mechanical Systems. MOEMS will yield spectacular new products for all of our once-isolated "islands of technology". This will bring new answers to all of the sciences and new products to all of the technologies. Can this really happen or is it beyond our capabilities? The good news is that MOEMS is already here. The digital projector for this presentation may even use MOEMS. A tiny module with over 1-million micro-mirrors may be switching light so rapidly that the eye is unaware of this incredible activity. Other MOEMS devices are moving into advanced telecommunications – today's most important market.

Today's most sophisticated MOEMS product contains well over a million moving optical parts making it the most complex machine on earth. A MOEMS chip is now in production that has more parts than the most sophisticated aircraft or rocket ever built. The individual micro-mirrors are so small, that a bacterium could reduce the pixel light intensity. But what is more remarkable is the fact that the device was mass-produced in a semiconductor foundry. Every wafer contains nearly 1-billion mirrors. How far will the new science of unification take us? It's too early to tell at this embryonic stage, but the real constraints are probably the self-imposed limits of imagination. Next, we will look at nano-technology in more detail.

The MEMS products, while fascinating and valuable, are incomplete until we add light, or optics. The addition of optical functionality gives us the full deck of technology cards to play the game of MOEMS. We now have the ultimate chip-level integration and it will enable true System on a Chip (SoC). Now we can potentially integrate just about everything – motion devices, optic systems, sound, chemical analysis, radio waves and computation. Some devices will send, receive and precisely control light beams, others will detect specific molecules and still others will mimic most of the human "senses". So if a logic chip can serve as the *brain*, MOEMS adds the *eyes, nose, ears* and other sensory input. And if that's not enough, MOEMS is also control – electrical, mechanical and electromagnetic. Continuing with our human analogy, MOEMS becomes the *hands and fingers* as these devices move internal parts and external objects. MOEMS is the technology for a next level of products for many decades to come. Single-chip ***merging of motion, sensing and computation*** is a major leap in technology. Figure 9 shows the world's most complex machine, the digital micro-mirror device from Texas Instruments in the USA. But the magic mirror systems have already moved into the Internet. Micro-mirrors and other MOEMS devices are being tested as optical switches to route photonic information along the World-Wide-Highway made mostly of glass. The day will soon be here when you will see a motion picture projected by MOEMS that arrived on the Internet as photonic data routed by MOEMS. Now let's look more closely at our faithful servants and messengers of technology – electrons and photons.

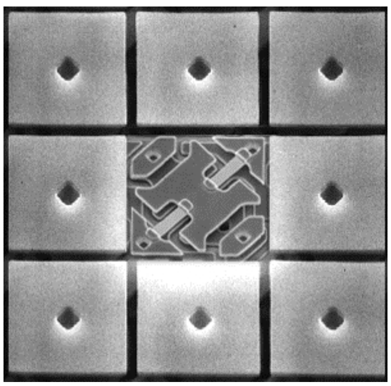

Figure 9 – Micro-Mirror MOEMS Chip – Texas Instruments (The center mirror is removed to see the internal structure)

There are many other MOEMS optoelectronics switch types that use other principles. Agilent has invented a bubble switch. Figure 10 shows the schematic for their thermally moved fluid "prism" that instantly redirects the light beam. Both TI and Agilent have built light-directing modules.

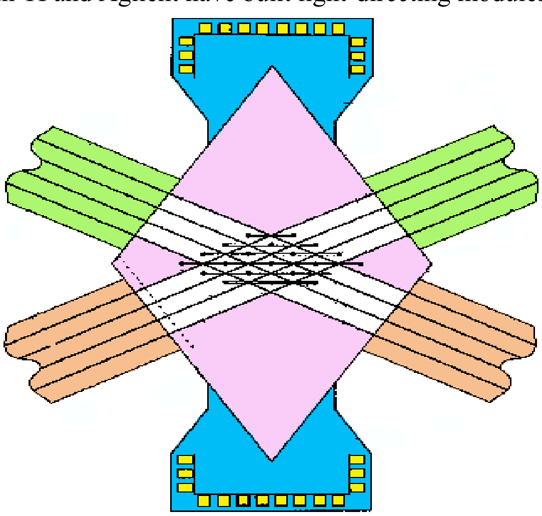

Figure 10 – MOEMS Bubble Switch (Agilent)

Figure 11 shows Lucent's 2-axis, or 3D optical switch array that is already in use as an OE switch. The 3D switch is more complex but can direct the incoming beam to any exit point. This requires substantially fewer mirrors than a 2-axis, off-on type of mirror.

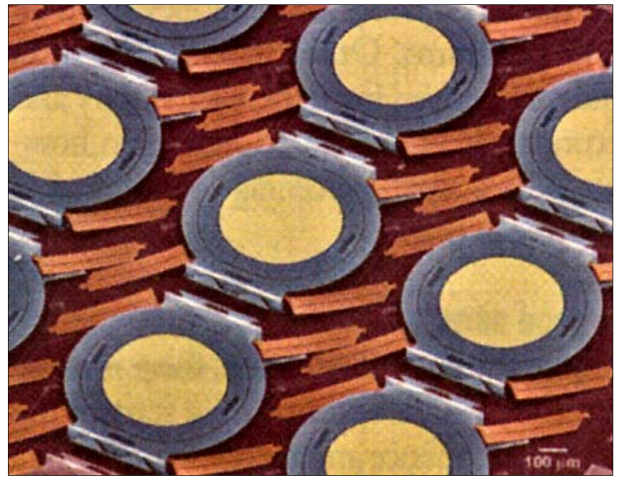

Figure 11 - 3D MOEMS Mirror – Lucent

The addition of mechanics to electronics and optics would seem to provide just what is needed for advanced OE technology. But electronics does not require mechanics to do electronic switching. Why can't we have an OE integrated circuit or optical IC? Before delving into that question, let's look at the differences between the basic elements of the two technologies, electrons and photons.

ELECTRONS VS. PHOTONS

We are all familiar with the affects of electrons and photons. Life on earth has relied on the photon for millions of years to receive energy and information. The photon brings us life-giving sunlight and visual data from near and very, very far. Giant telescopes examine photons that have journeyed through trillions of miles of space for billions of years to see the past. Photons stream through tiny optical fiber to transfer voice, music, e-mail and pictures around the world in the blink of an eye. If not encumbered by older switching technology, the photonic messages could circumvent the planet a half-dozen times during the moment it takes to make a single keystroke. The World Wide Hub of communications is where MOEMS will help us communicate at the speed of light.

The electron has mass and electrical charge that give it advantages but also limitations. The electron obediently follows our imposed pathways made of metal. The electron is also content to park along the route and wait at our command. All of these characteristics make it ideal for computing, transferring power and conversion to other forms of energy. This is why electrical and electronic products have worked so well to become all pervasive. But the electron becomes a very poor 2nd in the digital data marathon race.

The photon is weightless and has no electrical charge. It is relatively unreactive and travels at the speed of light (velocity is a little lower in glass, but more than 20-million meters/sec is still fast). And photons are always on the move refusing to park and rest. Photons are at the high frequency end of the Electromagnetic Spectrum that includes radio waves, x-rays and cosmic rays. Since bandwidth is directly proportional to frequency, photonics beats radio transmission by about 1-million times - 6 orders of magnitude. Thus, "Redtooth" (infrared wireless) beats Bluetooth by a factor of a million to one. If that's not enough, the low interaction photons can be highly multiplexed to boost this million times advantage by hundreds or even thousands. Data streams of different wavelengths ("colors") can be sent down the same strand of fiber and then split into separate signals at the other end. This mega-bandwidth boost is called Wave Division Multiplexing (WDM). The astonishing *million-times-a-thousand* bandwidth advantage over electronics makes photonics the indisputable communications champion, at least over long distances. A single 4 oz. strand of glass fiber carriers the same information that would require 33 tons of copper wire – 680 cables each containing 1800 copper wire pairs (according to Corning). So, should we forget about electronics? Not at all! Photons can't do it all and the best game in town is where electrons and photons meet. Let's look into the photon devices.

INTEGRATION OF PHOTONIC DEVICES?

We know how to deal with electrons. They efficiently follow conductive paths even when we make "wires" smaller and smaller. The electrons are great navigators, easily taking right angle corners and hairpin turns like seasoned racing drivers. Electrons are content to stop (capacitors) and also to create useful phenomenon like magnetic fields (inductors, motors, etc.). They've served us well as the basic unit of energy and signals in thousands of products. Integrated Circuits are based on electrons and the IC has proved to be exceedingly scalable as smaller paths continuously generate higher operating speeds.

The pure energy photon is the speed demon that will stop for no one (except for MIT who finally stopped photons in 2001). Photons are very difficult to store until someone invents the photon capacitor. While photons scream along the Internet Highway of glass, they are only good on the straightaway. No tight turns for photons or it's off the road and lost in space. Glass fiber, the copper wire equivalent for photons, can't be curved too tightly or the light will leak out. That's right! Photons cannot make a right-angle turn using fiber. If we were to convert electronic IC conductor traces to optical glass, it wouldn't work. The photonic or optical IC cannot use the same conduit principles suitable for electrons. New concepts are needed and perhaps we will just add mirrors or prisms by some mass-fabrication process. The integration of optics seems like a formidable challenge and will require considerable innovation.

PACKAGING

But let's assume that the optical IC has been perfected. Now let's package it. The package must allow photons to easily enter and exit while protecting the device that can be quite sensitive to moisture, oxygen and any contamination. Earlier, we discussed possible strategies for new MOEMS packages. This challenge is quickly becoming the manufacturing and economic bottleneck for photonics, but this is an area where the electronics industry can help. Perhaps wafer-level packaging is a good answer. Figure 12 shows a conventional OE hermetic package that is used today, but is costly.

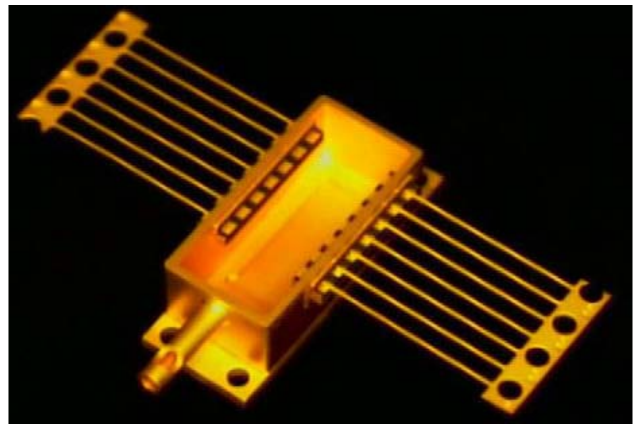

Figure 12 – Hermetic OE Package

But work is underway to develop low-cost OE packages including wafer-level types. It may not be necessary to use a full hermetic package, but one that has a slow leak rate that is acceptable. This could lead to the use of high-barrier organics, like liquid crystal polymers (LCP). Figure 13 show a wafer-level optical package from Shellcase.

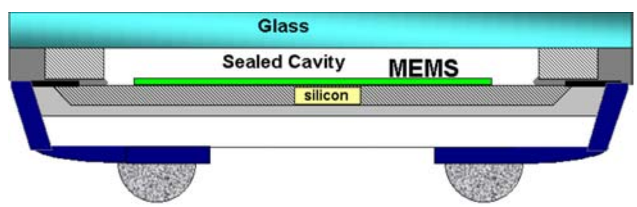

Figure 12 – OE CSP - Shellcase

ASSEMBLY

Let's now assume that we have a practical photonic package. All we have to do is assemble it. Now here is a big challenge. Electronic packages are soldered to boards very efficiently using highly automated lines. So photonics should just follow our great example, right? Alas, there is no Optical Solder! Photons are very fussy about junctions. Fiber connections are not generally made using a joining material although optical adhesives have been available for a long time. The optical junction must be almost perfect, essentially invisible, and adhesives have not succeeded to any extent. We should think of light as a wave and the fiber as a wave-guide. So the problem is more like trying to solder together RF wave-guides, but it's much more difficult. Consider trying to perfectly align two 9-micron wires (hair is 75-microns) and then mating them in such a way that no changes occur. A slight shift in refractive index can ruin the connection. Even minor stresses can degrade the light path properties. We may even need to deal with rotational alignment. And the light traveling inside the fiber may not even be at the center of the tiny core. Today, the best connections are made by carefully aligning fiber and fusing at high temperatures while constantly measuring the signal (active alignment). A single fusion joint can cost more than US$8.00 in labor that takes many minutes. Now compare this to our less-than-a-penny connection electronic joints. Of course, we may find ingenious ways to make photon connections or even use different kinds of pathways, but there are many challenges ahead. Perhaps photonic packages should use LEDs or VCSEL (Vertical Cavity Self-Emitting Lasers) for data links. Maybe a MEMS component could actively maintain optimum alignment.

FIBERLESS?

What about Bell's great Photophone idea? Did it ever go anywhere? Ironically, the modern Photophone has become popular in the last few years as a high-speed data link in metro areas. Transceivers are placed on buildings and customers can link up right through windows. The units have ranges of several miles and have been testing in fog-prone Seattle. Expect to see ceiling dome units in public places like airports, but don't call it Bluetooth. The infrared links to laptops, PDAs and cellular phones would aptly be called "Redtooth". Figure 13 shows a transmitter and Figure 14 shows a small network.

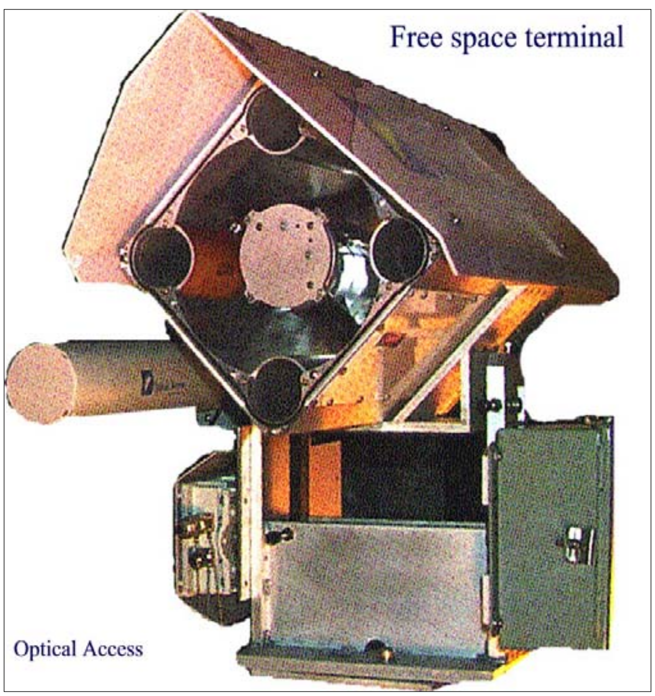

Figure 13 – Free-Space Optical Transmitter (Optical Access)

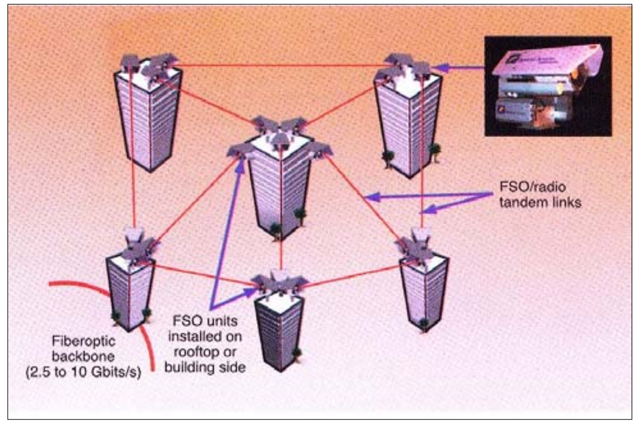

Figure 14 – Optical Network (Optical Access)

CONCLUSION

Optoelectronics has moved to the forefront during the last few years as the photonics-based Internet has become immensely popular. While OE has been around for decades, new demands have produced breakthroughs in all areas from new fibers to tunable lasers. The most exciting OE devices, and the most complex, are the MOEMS optical switches that are moving into Internet routing systems.

While OE devices are nothing short of incredible, there is almost no on-chip integration. The laws of optics and the many incompatible materials make the optical IC a very difficult challenge. Packaging is also a large issue, but efforts are underway to invent and develop lower cost OE packages.

OE assembly is said to be 25 to 30 years behind electronics and this statement is partially true. The lack of an "optical solder" and the need to fuse nearly invisible glass fibers makes OE connections and assembly tedious and expensive. While there may never be an optical soldering type process, automation is coming to the rescue. OE is an exciting field with great potential, but with very significant challenges. While there are selective opportunities, there are also landmines and the newcomer should tread cautiously. *Some of the "diamonds in the rough" are really glass priced as diamonds.*