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Moore's Law for Photonics and Beyond

Sensing and processing are intimately intertwined, yet the technologies we have developed for each are worlds apart. The world of processing is totally dominated by electronics, and silicon is the king of the electronics world. In contrast, the world of photonics (which deals with generating, controlling and detecting light and plays a major role in sensing) is based on a variety of different materials.

Some say the worlds of photonics and electronics will never meet. DARPA is about to do just that: bring the worlds of photonics and electronics into a seamless unison. The result will be a revolutionary advance of immense importance, with wide ranging applications of military interest in the fields of communications, sensors, radars, and wherever photonics and electronics intersect.

The human vision system is the ultimate interface of photonics and electronics. The eye and the brain work in perfect harmony. You sense me by photons, the quantized lightwaves that impinge on your retina. You recognize that I am a human being and not a robot because of the processing performed by your brain. The optical information received by the retina is quickly converted into electrical impulses. These impulses travel through the optic nerve to the visual cortex in the brain.

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The brain simultaneously adjusts the focus and direction of the eye toward objects of interest, performs a lookup to identify the objects, and stores the information for new objects.

Both eye and brain function as a single unit, with a seamless exchange of data between the photonic components in the eye and the electronic components in the brain. One could consider the retina/optic nerve as a single chip with dual functionality.

Seamless union of electronics and photonics is the ultimate goal of MTO's program for developing a single tiny chip of silicon that can not only manipulate and guide photons, but also convert photons into electrons and process the electrical signals. This program is called EPIC. Our goal is to leverage photonics to enhance the functionality of electronics, and vice versa, for significantly enhanced overall functionality. This would be a revolutionary advance that would bring a whole new realm of opportunities and usher in a new era of technology that will ultimately transform the internet, computing, communications, medicine, energy, nanotechnology, and much more.

What if I were to tell you that some day this technology will deny an enemy the tactical use of frequency-hopping, code-hopping, and broad spectrum techniques while simultaneously providing self-protection from enemy jamming?

What if I were to tell you that some day this technology will enable real time electronic warfare using a unit small enough to be carried by a Soldier?

The possibilities are limitless.

All these will be achieved with huge reductions in size, weight, and power consumption. It will enable new insertion opportunities for small form factor systems such as UAVs, microsatellites, unattended ground sensors, handheld communication systems, and covert implanted devices.

Of course, it is not quite as simple as it sounds, and there is much work to be done. We first need to extend the well-known Moore's Law of electronics to photonics.

In 1965, Gordon Moore made his famous observation that the number of transistors per integrated circuit doubles every couple years. That prediction, dubbed "Moore's Law," has been maintained and still holds true. Moore envisioned squeezing as many as 65,000 transistors on a single silicon chip by 1975. In fact, the Intel Pentium 4, released in November 2000, has 42 million transistors on a single chip. If we continue to follow Moore's Law, there will be an astounding 15 *billion* transistors on a single chip by 2018.

Photonics has come a long way since the early days of LEDs and lasers in the 1960s, and DARPA has played an important role every step of the way. We have seen the development of visible and near-infrared LEDs that changed short-range data communications. LEDs have affected displays in almost every possible arena, from automobiles, to moving message boards, to personal electronics, to military avionics.

The development of semiconductor lasers revolutionized data and voice communications. From compact disc players to undersea pump lasers, the semiconductor laser etched itself into the fabric of everyday life. The laser and other photonic devices enabled wavelength division multiplexing (WDM) optical networks that can accommodate ever-increasing internet traffic volumes. Invention of the vertical cavity surface-emitting laser (VCSEL) in the early 1990s was another revolutionary change. It paved the way for one- and two-dimensional arrays of devices, higher data rates, and reduced manufacturing costs, and enabled high capacity interconnects.

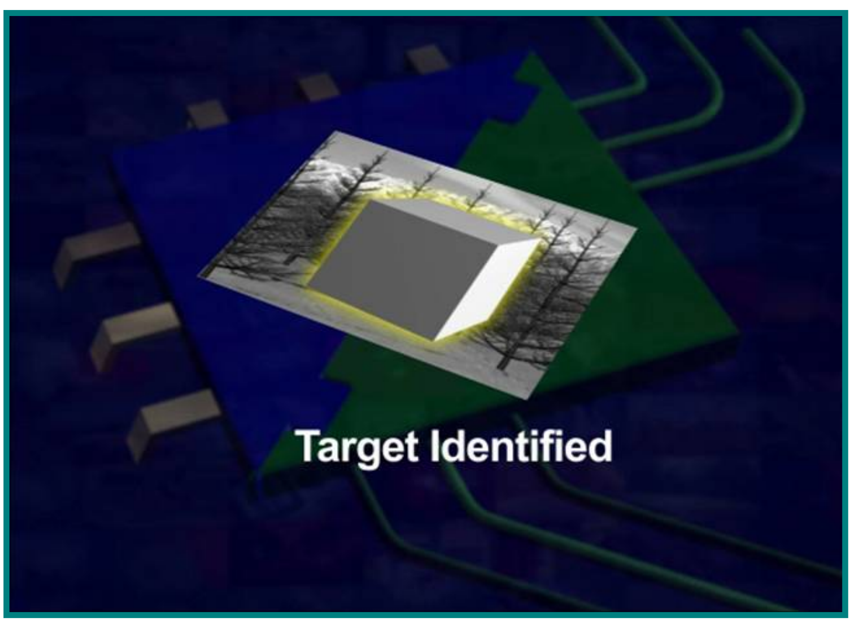
While demonstration of high performing discrete photonic devices is an important first step, it is not enough. We need to integrate multiple devices on a single chip. This can be achieved by making the devices smaller, more efficient ,and less power hungry. Unlike electronics, where there is a single building block in the form of a complementary metal-oxide semiconductor (CMOS) transistor, photonics needs multiple functionalities. Thus, we need not only active devices like laser and modulators, but also detectors, filters, multiplexers, wavelength converters, optical switches, and isolators. The current state of photonic technology is such that a variety of different materials platforms are needed for different device functionalities. To bring photonics technology to the next level, MTO has programs to demonstrate integration of multiple WDM functionalities on a single chip. MTO's program on optical packet switching is pushing the frontiers in this direction. To put photonics on the path of its own Moore's Law, we need to do all this and, at the same time, make these devices smaller, more efficient, and less power hungry. It will not be easy, but it will be worth the effort.

This, however, is only a part of the vision. We can envision going beyond Moore's Law for photonics. What if we could put photonics and electronics on a single chip?

Silicon, the king of electronics, is an indirect bandgap semiconductor. It is not considered an ideal photonic material because it does not emit or modulate light efficiently. Therefore, active photonic devices have been fabricated primarily in III-V semiconductors such as indium phosphide (InP) and gallium arsenide (GaAs). What if we could show that a complete set of high performance photonic devices *can* be fabricated in silicon using fully CMOS-compatible processing? The current 90-nm CMOS processing node allows structures to be created with sufficient smoothness and, hence, sufficiently low loss to make this possible. This is precisely one of the goals of EPIC.

A most exciting prospect is that as the CMOS foundries decrease the feature size to 65 nm to 45 nm and, ultimately, 10 nm, the photonic devices can ride this progress and continue to become smaller, faster, and less power hungry. The photonics Moore's Law would then outpace the electronic Moore's Law in approaching its ultimate limit of photon wavelength.

Exciting as this would be, this is not the end. Once high performance photonic circuits can be created in a CMOS-compatible manner, they can co-exist on the same of chip of silicon with electronic circuits. The goal of the EPIC program is to demonstrate functional, application-specific EPIC chips. This would put us on a path to achieving the vision of seamless harmony between electronics and photonics, of a single chip emulating the eye and the brain.



But this is also not the end of the road. Once we unify sensing and processing on a single chip, we can envision that photonics would play an ever-increasing role in processing. Photonics can, in principle, do enormous amount of preprocessing or parallel processing. The next step in the revolution would be to make photonics more and more intelligent.

Who can help me realize this vision? You?

We can bridge this gap together.