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White Paper

Introducing Intel's Advances in Silicon Photonics

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Research and Development at Intel

Intel's research into silicon photonics is an end-to-end program to extend Moore's Law into new areas, such as fiber optics. It aims to "siliconize" photonics by using Intel's manufacturing expertise to develop and build optical devices in silicon and bring PC economics to high-bandwidth optical communications..

Fiber optics use light to transmit data over a glass fiber. The primary benefit of using light rather than an electric signal over copper wiring is significantly greater capacity. Lightwaves can encode and deliver data significantly farther and faster than copper, and glass fiber can transmit numerous lightwaves simultaneously. Some fiber systems today, for example, can transmit 128 different data streams each on its own lightwave and each with a greater capacity than a corresponding copper wire. In addition, glass fiber has desirable physical properties: it is lighter and impervious to factors such as electrical interference and crosstalk that degrade signal quality on copper wires.

Photonics is the field of study that deals with light, especially the development of components for optical communications. It is the hardware aspect of fiber optics; and due to commercial demand for bandwidth, it has enjoyed considerable expansion and development during the past decade. During the last few years, researchers at Intel have been actively exploring the use of silicon as the primary basis of photonic components. This research has established Intel's reputation in a specialized field called silicon photonics, which appears poised to provide solutions that break through longstanding limitations of silicon as a material for fiber optics. In addition to this research, Intel's expertise in fabricating processors from silicon could enable it to create inexpensive, high-performance photonic devices that comprise numerous components integrated on one silicon die.

This white paper discusses Intel's quest to "siliconize" photonics by using silicon to create these building blocks. It then discusses Intel's recent breakthrough: a device made entirely from silicon that encodes data on light at 50 times the data rate previously achieved in silicon.

Basic Photonics

To appreciate the nature of Intel's announcement, it is important to understand how fiber optics transmit and receive data and the role photonic components play in this process.

Light, as we see it in our lives, is transmitted at different wavelengths. At one end of the visible spectrum are the wavelengths we see as red; at the other end, are those we see as violet. Between them exist all the visible colors, each at its own wavelength. Beyond the low end of the visible spectrum are ultraviolet wavelengths, and beyond the upper end are infrared. Today's fiber optic lasers primarily use infrared wavelengths for communication. (See Figure 1.)

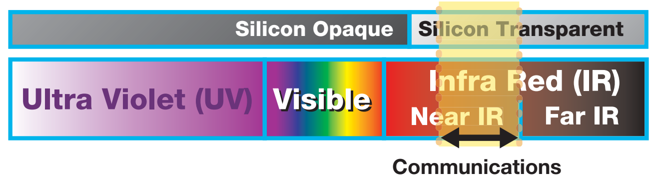

Figure 1. Fiber optics today use infrared wavelengths, which lie outside the visible spectrum. Due to the characteristics of fibers, certain wavelengths, shown in this chart, are particularly suited to fiber optics.

Figure 2 shows an example layout of a basic transmitter. A laser creates a beam of light onto which a modulator encodes data. The light is then transported via a glass fiber to a destination of interest. Fibers often carry multiple wavelengths of light simultaneously-each one encoded with its own data stream. These wavelengths are combined by a device called a multiplexer and placed on the fiber, as shown.

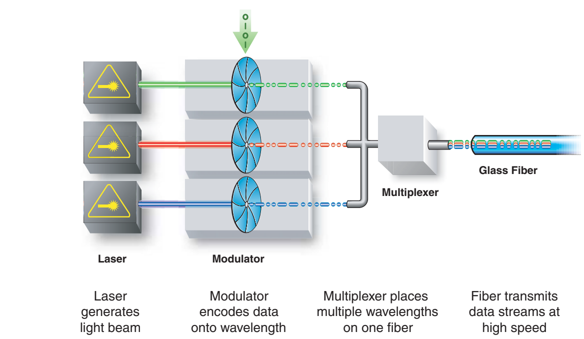

Figure 2. The basic components of fiber optic transmission.

On the receiving end, (shown in Figure 3) the laser light is demultiplexed, that is, split into individual wavelengths. Each wavelength is routed to a separate photodetector, which converts the light into an electric signal, which can then be routed to the host logic for processing.

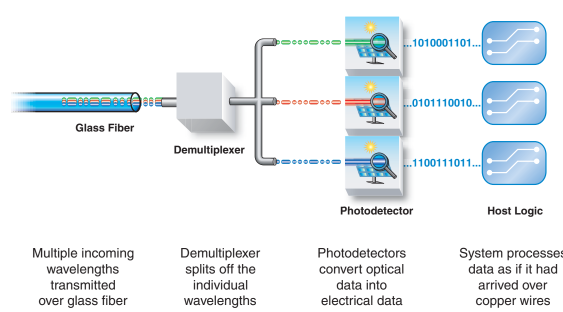

Figure 3. Processing wavelengths on the receiving end.

Fiber optic systems may also use other items such as mirrors, splitters, and switches to manipulate the light or add and drop the optical signal to various locations.

Optical devices typically have been made from exotic materials such as such as gallium arsenide and indium phosphide that are complicated to process. In addition, many photonic devices today are hand assembled and often require active or manual alignment to connect the components and fibers onto the devices. This non-automated process tends to contribute significantly to the cost of these optical devices. With the recent slow down of the telecom industry and the subsequent focus on price/performance for optical devices, these factors have emerged as important limitations. The silicon photonics research at Intel aims at establishing whether manufacturing processes using silicon can overcome some of these limitations.

Silicon Photonics

Silicon has numerous qualities that make it a desirable material for constructing small, low-cost, optical components: it is a relatively inexpensive, plentiful, and well understood material for producing electronic devices. In addition, due to the longstanding use of silicon in the semiconductor industry, the fabrication tools by which it can be processed into small components are commonly available today. Because Intel has more than 35 years of experience in silicon and device fabrication, it finds a natural fit in exploring the design and development of silicon photonics.

As stated previously, the goal of Intel's research is to siliconize photonics—specifically to build in silicon all the functions necessary for optical transmission and reception of data. The goal is then to integrate the resulting devices onto a single chip. An analogy can be made that such optical chips hold the same relationship to the individual components as integrated circuits do to the transistors that constitute them: they provide a complete unit that can be manufactured easily and inexpensively using standard silicon fabrication techniques. Intel has recently been able to demonstrate basic feasibility to siliconize many of the components needed for optical communication. The most recent advance involves encoding high-speed data on an optical beam.

Intel's Latest Breakthrough: High-Speed Silicon Modulation

The simplest method of performing modulation (the process of encoding data onto a wavelength of light) is to turn the laser on and off at high speeds ("on" representing a 1 bit, "off" a 0 bit). This direct modulation approach, however, has the drawback of constantly heating and cooling the laser. The constant changes in temperature can create problems—such as shifts in the wavelength the laser generates—that distort the optical data. Another option is the use of an external modulator that acts as a shutter that opens and closes at high speeds to encode the data on the light passing through the device.

Modulators that operate at speeds fast enough to be of interest to communication networks today (that is, 1GHz or faster) are not currently made from silicon. Although optical modulators have been fabricated in silicon, they tend to be considerably slower than what is required for even basic enterprise communication. The fastest reported silicon-based modulator has a top modulation speed of only about 20MHz—significantly slower than today's off-the-shelf Ethernet adapters. This limitation is a function of how the light beam is modulated within its silicon channel. Specifically, previous approaches turned the light on and off by using a diode to inject electrical current into the silicon conduit through which the light was traveling.

Intel's long experience with silicon fabrication led it to examine other approaches. In the course of these investigations, Intel discovered that complimentary metal oxide semiconductor (CMOS)—the same technology used in all Pentium® 4 processors today—could be used to modulate the light at much higher speeds. The transistor-like structure can be embedded in the optical waveguides (the passageways through which the light travels in silicon).

Rather than turning the laser on and off, this all-silicon modulator uses a technique called phase shifting to encode the data by changing the brightness of the lightwave. The modulator breaks the light beam into two smaller beams. It then makes the lightwaves of one beam out of sync (that is, out of phase) with those of the other; then, it merges the beams back together. This unified lightwave bears the imprints of both beams, which results in the light appearing to go and off (see Figure 4). This on-and-off activity is then translated into patterns of 1s and 0s. As shown in the figure, the phase shifting amplifies the light at certain points and negates it at others: hence the wave's amplitude (how strong or bright it is at any given moment) is modulated (that is, modified). This amplitude modulation (AM) is similar to the technique used by AM radios to encode sound on a broadcast signal: the wave is made weaker or stronger to encode changes in pitch of the sound riding on the base frequency to which the radio is tuned.

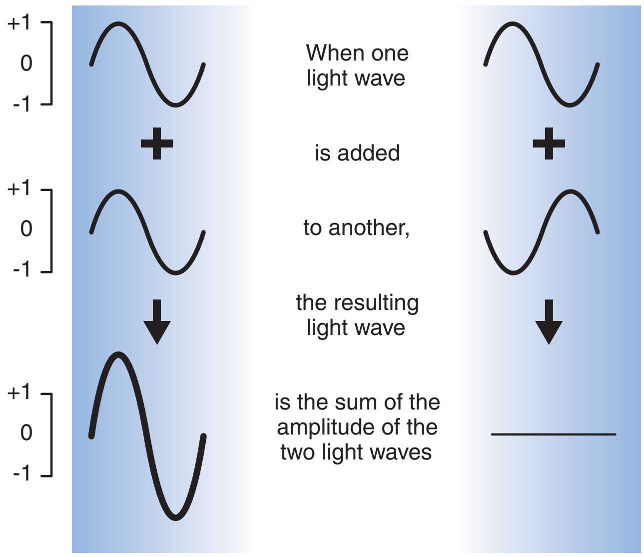

Figure 4. When two light waves come together the resulting lightwave is the sum of the two waves. So, if two light waves are perfectly in sync or in phase (left column), the result is a wave that is twice as bright; if the two waves are completely out of sync (out of phase as in the right column) the result is no light. Noise-canceling headphones work on the same principle: they produce a sound wave that cancels specific sound waves.

A basic diagram of how this phase shifting is applied to modulate a light beam in silicon is shown in Figure 5. A proof of concept of a CMOS-based modulator using this design was demonstrated by Intel in early 2003.

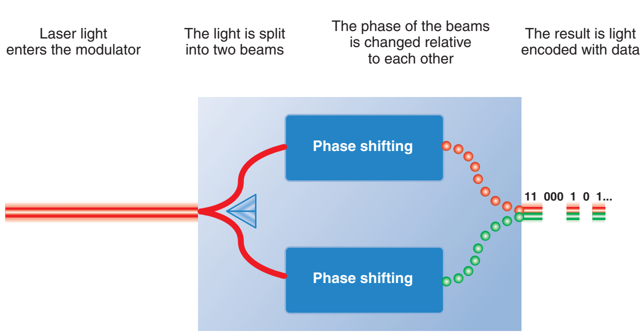

Figure 5. The entering light is split into two beams and the phase of each is shifted. When the two beams are combined, the resulting effect is the encoding of data onto the lightwave.

Intel is now demonstrating its latest advance: a version of this phase-shifting technique that can modulate data at speeds in excess of 1GHz. This rate is more than a 50-fold increase over the previous threshold of about 20MHz. Intel believes this technology can be extended to run at even higher speeds in the future, possibly to 10GHz and beyond. This breakthrough could move silicon photonics into important new areas. For the first time, silicon-based optical devices may be able to deliver the bandwidth load formerly managed only by high-end, expensive systems. The key concept here is that fiber optic capacity becomes available inexpensively.

The Optical Future

As Moore's Law continues to push microprocessor speeds, and as increasing volumes of data are sent across the Internet, the demands placed on network infrastructure will increase significantly. By taking advantage of silicon photonics, new products can scale bandwidth availability to meet this demand.

In addition, due to the low cost of silicon solutions, we can expect that servers and high-end PCs might one day come standard with an optical port for high-bandwidth communication. Likewise, other devices will be able to share in the bandwidth explosion provided by the optical building blocks of silicon photonics.

Intel's silicon photonics research is an end-to-end program that extends Moore's Law into new areas. It brings the benefits of CMOS and Intel's volume manufacturing expertise to fiber optic communications. The goal is not only achieving high-performance in silicon photonics, but doing so at a price point that makes the technology a natural fit-even an automatic feature—for all devices that consume bandwidth. Intel's breakthrough silicon modulator will undoubtedly contribute to the reality of this vision.

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