Faster than a Speeding Bullet

by Barry Olney
IN-CIRCUIT DESIGN PTY LTD AUSTRALIA

In a previous *Beyond Design* column, Transmission Lines, I mentioned that a transmission line does not carry the signal itself, but rather guides electromagnetic energy from one point to another. The speed of a computer does not depend intrinsically on the speed of electrons, but rather on the speed of energy transfer between electronic components. Electron flow in a multilayer PCB is extremely slow—about 10 mm per second—so, how does the signal travel so fast, how fast does it actually transfer information and what are the limitations?

In optical communications, electrons don't carry the signal—photons do. And we all know that photons travel at the speed of light. So surely, optical fibers must transmit information much faster than copper wires or traces on a multilayer PCB? Actually, photons and electrons transmit data at the same speed. The limiting factor is the relative permittivity (dielectric constant) of the medium in which the signal propagates.

An optical fiber is a cylindrical dielectric waveguide made of low-loss materials such as fused silica glass. It has a central core in which light is guided, and embedded in an outer cladding of slightly lower refractive index. The silica glass used has a dielectric constant (Er or Dk) = 3.78 @25GHz. Whereas, for instance, Panasonic's new Megtron 7, low Dk, glass PCB laminate

Figure 1: An FA-18 approaches the speed of sound. The white halo consists of condensed water droplets formed by the sudden drop in air pressure behind the shock cone around the aircraft. (Courtesy of the U.S. Navy)

has an Er = 3.3 at the same frequency. The dielectric material determines the velocity (v) of propagation of the electromagnetic energy:

$$v = \frac{c}{\sqrt{Er}}$$

where the speed of light (c) is 3x10^8 m/s.

Substituting the numbers, the optical fiber has a velocity of propagation of 154.6x10^6 m/s compared to 164.8x10^6 m/s for Megtron 7. So believe it or not, the PCB substrate, in this case, will actually transfer the signal faster than an optical fiber. However, the dissipation factor (dielectric loss) of silica is 0.00002 whereas Megtron 7 is only 0.003, which limits the bandwidth. However, this is still fairly low loss compared to standard FR-4 of 0.02.

Fibers have a number of advantages over copper, including higher bandwidth, lower loss, immunity to electromagnetic interference. There is also no crosstalk between signals in different optical cables. Further, non-armored fiber cables do not conduct electricity, which makes them ideal in high-voltage environments or structures prone to lightning strikes and for preventing ground loops.

Figure 2 illustrates a rigid PCB substrate with an embedded optical polymer waveguide. This novel structural design offers potential solutions for low-cost and high-performance semiconductor circuits with optical devices to realize wide bandwidth and low-profile optoelectronic packaging for chip-to-chip optical interconnect applications. The vertical cavity surface emitted laser (VCSEL), driver, and serializer chip are 3D stacked and then attached to one end of the embedded optical polymer waveguide in the PCB. Similarly, the photo-diode detector, trans-impedance amplifier (TIA), and deserializer chips are also stacked and then attached on the other end of the waveguide. Although this system has the same communications speed as a typical trace based interconnect, it potentially exhibits wider bandwidth and much lower noise.

The actual velocity of electrons through a conductor is measured at an average speed called the “drift speed.” The charge carriers (electrons) move very slowly; however, the “knock-on” effect is very fast as it follows the electromagnetic field. When one electron is forced to move, it bumps into its neighbor making it move and so on: the domino effect. The energy propagates as an electromagnetic wave.

The electrical effects that we observe, such as lights coming on immediately when a switch

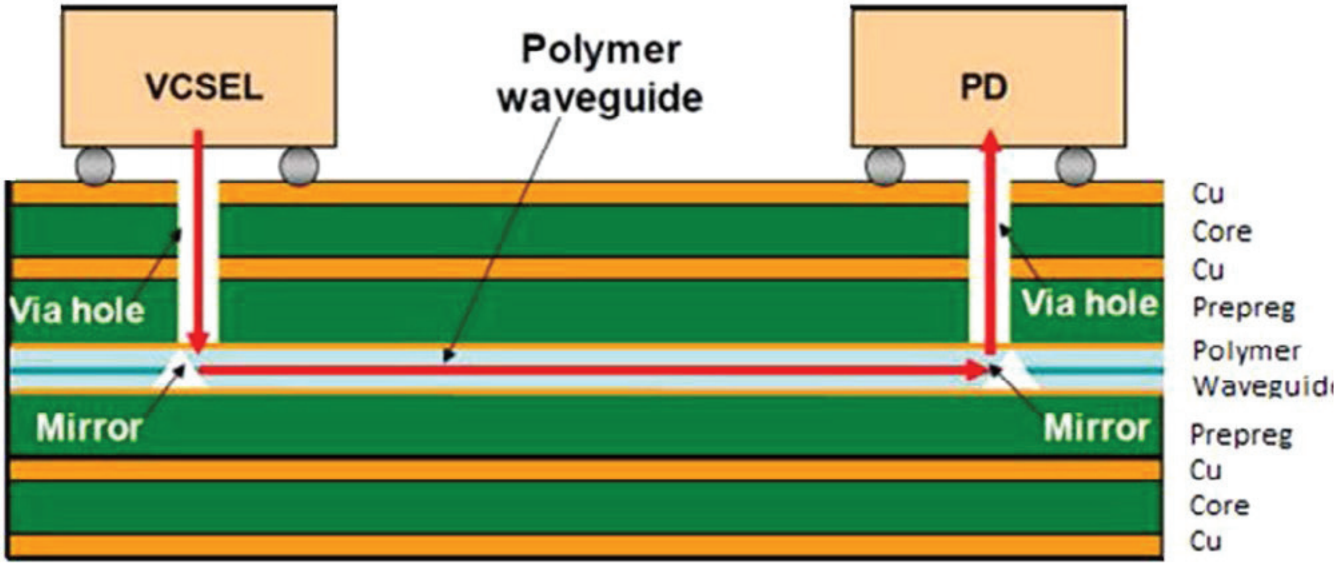

Figure 2: Low-cost, high-performance optoelectronic system embedded into an organic laminated substrate. (Source: Lau, Zhang, Lee)

is closed, are due to this knock-on effect. This explains the observation that a complete circuit is needed for current flow. If one charge carrier cannot cross a gap in the circuit, all the other charge carriers behind cannot move either and current does not flow anywhere in the circuit. This scenario explains DC and low-frequency circuits that have a single point ground reference (as taught in Circuit Theory 101).

However, above 100KHz parasitic capacitance and inductance become significant allowing current to flow in multiple paths. In a multilayer PCB, the electric field charges each section's R-L-C-G elements; in turn, as the rising edge propagates along the transmission line with the return current from each section, flowing back to the source. Then as the pulse passes, the falling edge discharges each section's capacitance. By the time the signal wave reaches the load, it has established multiple paths of return current along the PCB planes.

The speed at which the signal travels down the conductor really has nothing to do with the drift speed of the electrons. The signal is an electromagnetic wave that travels at about half the speed of light. The electrons serve to guide the wave down the wire. It is the movement of the electromagnetic field or energy—not voltage or current that transfers the signal. The voltage and current exist in the conductor, but only as a consequence of the field being present as it moves past.

We have established the fact that signals travel at the same speed, given the same medium, but what limits the bandwidth? Let me use a metaphor to explain: The speed of sound is much slower than that of light at 343.2 m/s in air. However, this isn't the speed of the channel—it is its latency. That is, if you are 343 meters away, you will hear me one second after I speak. That reveals nothing about how fast I can communicate with you, which is limited by

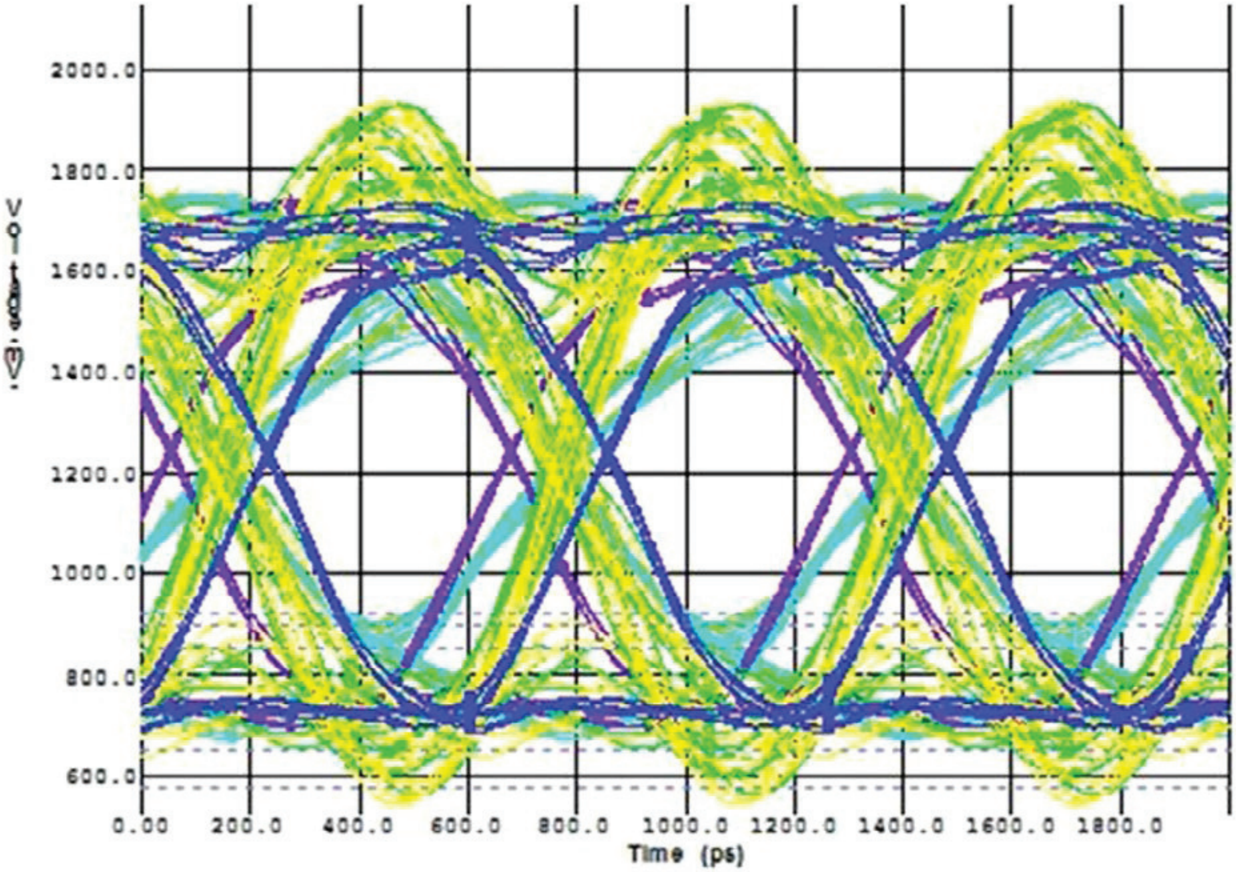

Figure 3: Eye diagram displaying jitter and noise in Mentor Graphics' HyperLynx tool.

how effectively I can speak, and how well you can hear me.

If we are in a quiet room, I can probably speak very quickly and you can still hear me. If we are far apart, or the environment is noisy, I will have to speak louder, more slowly and clearly. With electrical communications the situation is much the same. The speed limit is not due to the latency, but rather how fast one end can transmit with the other end still being able to reliably receive. This is limited by noise picked up from the environment and distortions introduced by the medium—the noise margin.

It is the signal-to-noise ratio (SNR) that bestows optical fibers with a higher bandwidth than other transmission mediums, given the same speed of transmission. One of the most important ways to determine the quality of a digital transmission system is to measure its bit error ratio (BER). The BER is calculated by comparing the transmitted sequence of bits to the received bits and counting the number of errors. Very small changes of the SNR (in the order of a dB) can cause very large changes in the BER.

An eye diagram is a common indicator of the quality of signals in high-speed digital transmissions. An oscilloscope generates an eye diagram by overlaying sweeps of different segments of a long data stream driven by a master clock. In a simulation tool such as Mentor Graphics' HyperLynx, a pseudo-random bit stream is generally used to produce the overlapping sweeps as in Figure 3. In an ideal world, eye diagrams would look like rectangular boxes. In reality, communications are imperfect, so the transitions do not lie precisely on top of each other, and an eye-shaped pattern results. However, in Figure 3, we can see the jitter (horizontal miss-alignment) and the distortion set by the SNR (vertical miss-alignment).

In high-speed multilayer PCBs, we need to select the material with the lowest dielectric constant (Dk) and the lowest dielectric loss (Df) in order to achieve the maximum bandwidth which is the 5th harmonic of the fundamental frequency. (The dielectric materials library integrated in to the ICD Stackup Planner, has 20,000 rigid-flex materials up to 100GHz to choose from. This makes selecting the right material for your application easy.)

As frequency increases, so does the bandwidth. However, we must select the most efficient frequency for the particular transmission channel. If the frequency is too low or too high, we lose the signal's power. This is due to how the medium responds to different levels of charge energy. In general, the amount of information you can transmit is proportional to the rate the channel can respond. Basically, one has to stay within a certain limit depending on the medium. It just so happens that the higher the operating frequency and the lower the loss, the easier it is to get wider bandwidths and hence more data reliably through the channel.

Points to Remember:

- A transmission line does not carry the signal itself; it guides electromagnetic energy from one point to another.
- Electron flow in a multilayer PCB, is extremely slow—a few meters per second.
- Photons and electrons transmit data at the same speed. The limiting factor is the relative permittivity of the medium in which the signal propagates.
- Fibers have a number of advantages compared to copper, including higher bandwidth, lower loss, and immunity to electromagnetic interference.
- The charge carriers (electrons) move very slowly; however the knock-on effect is very fast as it follows the electromagnetic field.
- DC and low-frequency circuits have a single point ground reference. However, above 100KHz parasitic capacitance and inductance become significant allowing current to flow in multiple paths.
- The speed at which the signal travels, down the conductor, really has nothing to do with the drift speed of the electrons. The signal is an electromagnetic wave that travels at about half of the speed of light. The electrons serve to guide the wave down the wire.
- It is the signal to noise ratio (SNR) that bestows optical fibers with a higher bandwidth than other transmission mediums, given the same speed of transmission.

- One of the most important ways to determine the quality of a digital transmission system is to measure its bit error ratio (BER).
- An eye diagram is a common indicator of the quality of signals in high-speed digital transmissions.
- In high-speed multilayer PCBs, we need to select the material with the lowest dielectric constant (aka Dk) and the lowest dielectric loss (Df) in order to achieve the maximum bandwidth.
- The higher the operating frequency and the lower the loss, the easier it is to get wider bandwidths. **PCBDESIGN**

References

1. Barry Olney, Beyond Design: Matched Length Does not Equal Matched Delay, Transmission Lines

2. Robert Dahlgren: Noise in Fiber Optic Communications Links

3. Lau, Zhang, Lee: Opto-electronic Interconnect in Organic Substrate

4. Bruce Archambeault: PCB Design for Real-World EMI Control

5. Howard Johnson: High-speed Signal Propagation

6. www.physics.stackexchange.com

7. Alan Finkel: Cosmos, Issue 61, "Silicon is King"

8. The ICD Stackup and PDN Planner: www.icd.com.au

Barry Olney is managing director of In-Circuit Design Pty Ltd (ICD), Australia. This PCB design service bureau specializes in board-level simulation, and has developed the ICD Stackup Planner and ICD PDN Planner software. To read past columns, or to contact Olney, click here.

Scientists Bridge Different Materials by Design

In an advance reported in Nature Chemistry, scientists at the University of Liverpool have shown that it is possible to design and construct interfaces between materials with different structures by making a bridge between them.

It is usually possible to make well-controlled interfaces when two materials have similar crystal structures, yet the ability to combine materials with different crystal structures has lacked the accurate design rules that increasingly exists in other areas of materials chemistry.

The design and formation of an atomic-scale bridge between different materials will lead to new and improved physical properties, opening the path to new information technology and energy science applications amongst a myriad of science and engineering possibilities. For example, atoms could move faster at the interface between the materials, enabling better batteries and fuel cells.

Liverpool Materials Chemist Professor Matthew Rosseinsky said, "When we try to fit materials together at the atomic scale, we are used to using the sizes of the atoms to decide which combinations of materials will "work" i.e. will produce a continuous well-ordered interface.

"The project team added in consideration of the chemical bonding around the atoms involved, as well as their sizes, as a key design step. This allowed the selection of two materials with different crystal structures yet with sufficient chemical flexibility to grow in a completely ordered manner throughout the interface between them.

"This was achieved by the formation of a unique ordered structure at the interface which did not correspond to either material but contained features of both of them, an atomic-scale bridge."

It is possible to construct a flexible block, which will fit with both materials, and bridge the gap between them, like the blue blocks bridge the gap between the red and green ones.