The Wavelength of Electromagnetic Energy

Beyond Design

by Barry Olney, IN-CIRCUIT DESIGN PTY LTD / AUSTRALIA

The speed of light is the one universal physical constant that we are yet to break. It is the limit of the velocity at which conventional matter and information can attain in our universe—without warping space-time, of course. At a lightning 299,792,458 m/s, it is the maximum speed at which massless particles (or waves) of light, electromagnetic energy, and gravitational waves travel in a vacuum. In this month's column, I will look at how to simply measure the speed of light and how the wavelength of electromagnetic energy relates to the multilayer PCB.

One morning recently, whilst eating my vegemite toast (as Australians do), I was reading my weekly *New Scientist Magazine* and came across an interesting article on how to measure the speed of light using a chocolate bar and a microwave oven. Here's how it works.

A microwave oven's magnetron (RF transmitter) oscillates at 2.45 GHz. Electromagnetic energy in this frequency range has an interesting property: It is absorbed by water, fats, and sugars. The microwaves, in the turned cavity, penetrate the food and excite the molecules heating the food throughout—provided the turntable is rotating. But for this exercise, the chocolate bar needs to be stationary, so remove the turntable.

Since the chocolate bar is not rotating, the microwaves are not evenly distributed throughout the bar, and regions of chocolate will begin to melt in the high-intensity areas. Chilling the bar first makes the molten areas more distinct. This will take approximately 50 seconds on high power. Take care not to exceed 60 seconds, or you may have a mess to clean (lick) up.

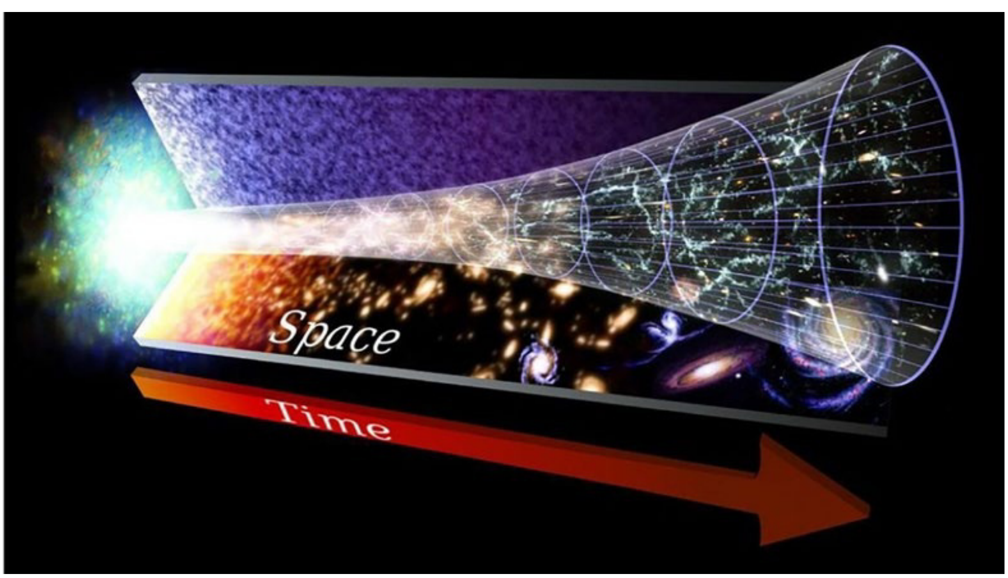

Figure 1: Half wavelength between hot spots. (Source: NASA Goddard Space Flight Center)

Electromagnetic energy travels in a wave through a vacuum or air at the speed of light. The distance between the peaks of the wave is the wavelength of the energy. As the wave travels, the peaks and troughs heat the chocolate. By measuring the distance between these hot spots, one can determine the half wavelength of the energy (Figure 1). You should get about 60 mm between the melted globs. I got 58 mm after 45 seconds. However, there is plenty of leeway in the dubious accuracy of my plastic ruler and failing eyesight. Doubling this (120 mm) gives you the wavelength related to a frequency of 2.45 GHz. The following equation is used to calculate the velocity (v), where f is frequency and lambda (λ)is the wavelength.

Equation 1:

$$v = f\lambda = 2.45\text{GHz} \times 0.12\text{m} = 294{,}000{,}000 \text{ m/s}$$

For an extremely rough measurement, this is very close to the actual velocity of light (299,792,458 m/s). Note that light will travel a little slower in the air than a perfect vacuum.

Now, let's look at how this relates to the speed of electromagnetic energy in multilayer PCBs. If you have a digital signal running at a clock rate of 2.45 GHz, then one would expect the wavelength to be 120 mm. Wrong! Unfortunately, the relative permeability or dielectric constant (Dk) of the surrounding materials impacts the velocity of propagation at the speed of light (c).

Equation 2:

$$v = f\lambda = \frac{c}{\sqrt{Dk}}$$

A vacuum has a Dk = 1, air = 1.0006 and typical FR-4 = 4. Then, solve Equation 2 for the wavelength, including the Dk of the dielectric material:

Equation 3:

$$\lambda = \frac{c}{f \; x \; \sqrt{Dk}} = \frac{299{,}792{,}458}{2.45\text{GHz} \; x \; \sqrt{4}} = 61 \text{ mm}$$

Therefore, the FR-4 material in a stripline configuration slows the propagation speed and decreases the wavelength of the electromag-

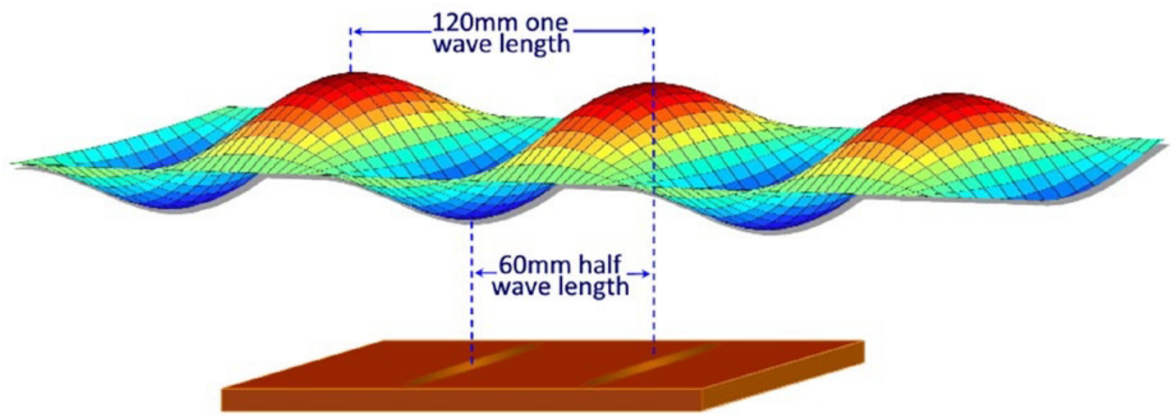

Figure 1: Half wavelength between hot spots.

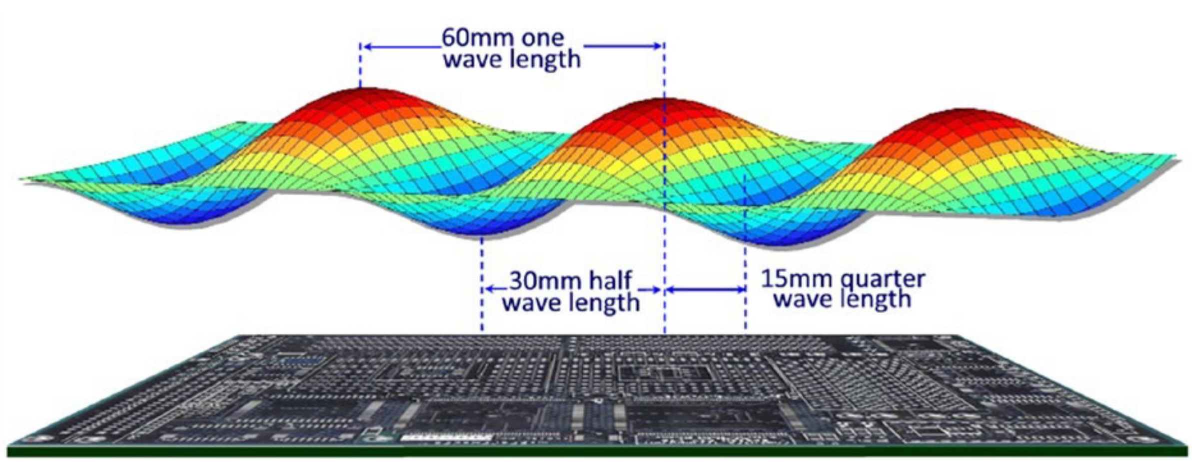

Figure 2: The wavelength of a 2.45-GHz signal on a PCB inner stripline layer.

Figure 3: Comparison of Dk per layer and relative velocity.

netic wave down by about half (Figure 2). But that all depends on the exact dielectric constant of the surrounding materials.

For the top layer 1, the electromagnetic energy travels in a combination of prepreg, solder mask, and air (Figure 3). The effective Dk will be around 2.68 with a propagation speed of 1.83 x 10^8 m/s. For layer 4, there is a combination of prepreg and core with an effective Dk of 4.03 and a speed of 1.49 x 10^8 m/s. This should be simulated by a field solver, as it depends on the combination of materials and their Dks, order, and thickness. From this, one can see that the propagation speed of the electromagnetic energy is always faster on the outer microstrip layers than the inner stripline layers.

At high frequencies, short traces (particularly stubs or unterminated traces) on a PCB can act as a monopole or loop antenna. Differential-mode radiation is the electromagnetic radiation caused by currents consisting of harmonic frequency components flowing in a loop in the PCB. The radiation is proportional to the current loop area and the square of the frequency of the signal. Common-mode radiation is the electromagnetic radiation caused by current flowing in an unterminated trace (or terminated with a high-input impedance device) and may require load terminating resistors to eliminate reflections. The radiation resembles that of a monopole antenna, and the magnitude is proportional to the current per line length and frequency.

Trace antennas form a monopole with a quarter wavelength ($\lambda/4$) at the resonant frequency. Monopoles require a ground plane; this forms the other quarter wavelength to radiate efficiently, which is not desirable in this case. It functions as an open resonator, oscillating with standing waves along its length. The radiation pattern is practically omni-directional.

Unfortunately, the high-frequency components of the fundamental (lowest frequency in a complex wave) radiate more readily because their shorter wavelengths are comparable to trace lengths, which act as antennas. Consequently, although the amplitude of the harmonic frequency components decreases as the frequency increases, the radiated frequency varies depending on the characteristics of the antennas/traces.

At 2.45 GHz, an 18-mm trace on the outer, microstrip layers may radiate while on the inner stripline layers, 15 mm (600 mils) is sufficient. And as we increase the frequency to 10 GHz, the maximum length is just 3.75 mm (150 mils), which is incredibly short. Stripline traces are embedded between two planes, which dramatically reduces radiation with the exception of the fringing fields from the edge of the board. However, the outer microstrip layers will radiate; hence critical, high-speed traces should be avoided on these layers.

Since the wavelength of electromagnetic energy depends on the signal frequency and dielectric constant of the surrounding materials, a low Dk (circled in Figure 4) is preferred for high-speed design. Fortunately, low-loss materials generally have this characteristic.

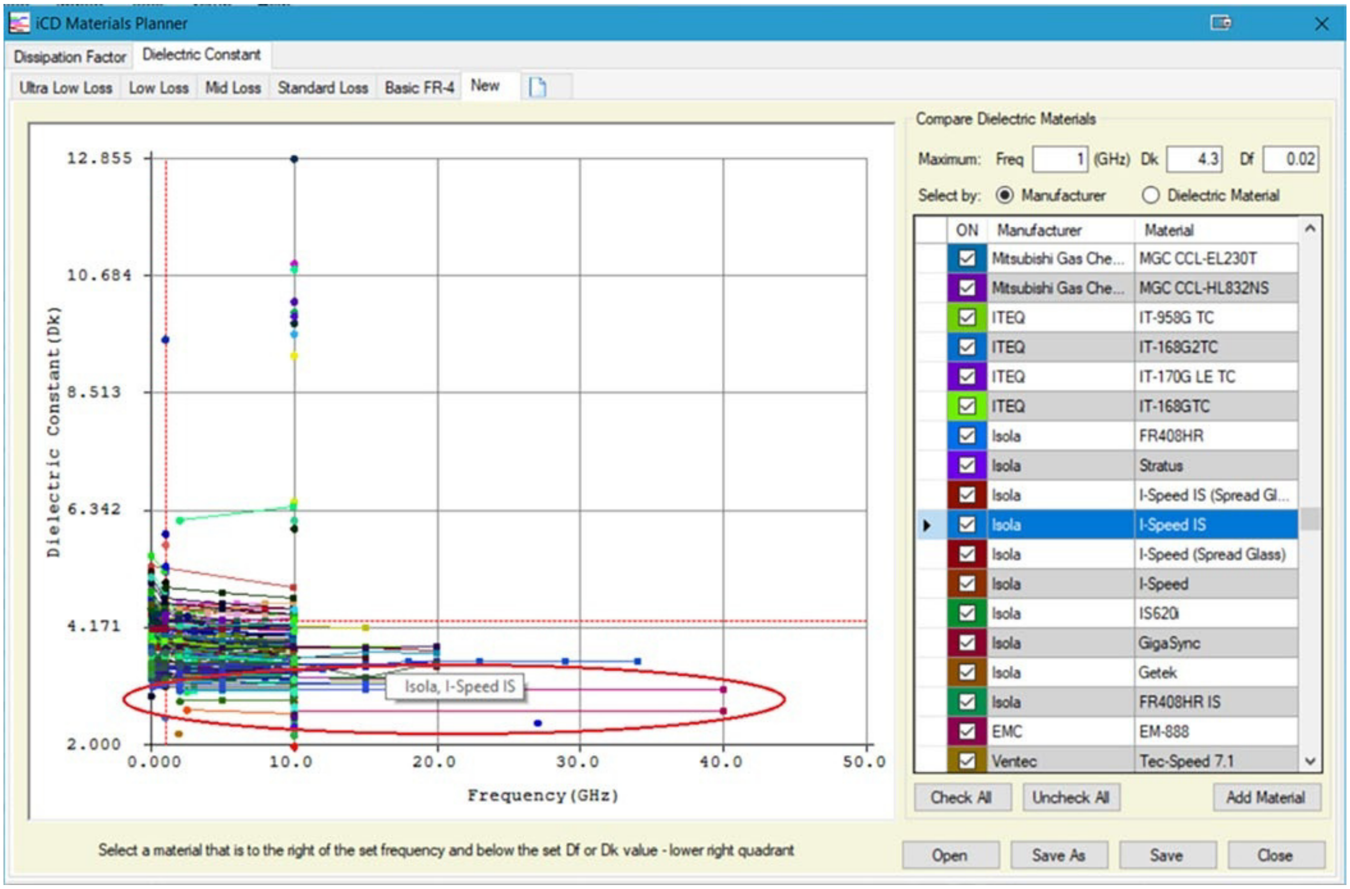

Figure 4: Plot of dielectric constants of high-speed materials (iCD Materials Planner).

Key Points

- Microwave energy is absorbed by water, fats, and sugars.
- Electromagnetic energy travels in a wave through a vacuum or air at the speed of light.
- The distance between the peaks and troughs of the energy is a half wavelength.
- The dielectric constant of the surrounding materials impacts the velocity of propagation of the signal.
- The FR-4 material in a stripline configuration slows the propagation speed and decreases the wavelength of the electromagnetic wave down by about half.
- In a microstrip (outer layer), the electromagnetic energy travels in a combination of prepreg, solder mask, and air, which reduces the effective Dk.
- In a stripline, there is a combination of prepreg and core.
- The propagation speed of the electromagnetic energy is always faster on the outer microstrip layers than the inner stripline layers.
- At high frequencies, short traces (particularly stubs or unterminated traces) on a PCB can act as a monopole or loop antenna.
- Trace antennas form a monopole with a quarter wavelength (λ/4) at the resonant frequency.
- High-frequency components of the fundamental radiate more readily because their shorter wavelengths are comparable to trace lengths.
- Outer microstrip layers will radiate; hence critical, high-speed traces should be avoided on these layers.
- A low-Dk material is preferred for high-speed designs.

Further Reading

- Barry Olney, "EMC Design for High-Speed PCBs," *Printed Circuit Design Magazine*, 1996.
- *New Scientist Magazine*, Issue 3285, June 6, 2020
- Wikipedia, "Speed of light."
- Amit Bahl, "Signal speed and propagation delay in a PCB transmission line," June 19, 2018.
- Roshni Prasad, "PCB Trace vs. Chip Antenna Design Considerations," Abracon LLC.

Barry Olney is managing director of In-Circuit Design Pty Ltd (iCD), Australia, a PCB design service bureau that specializes in board-level simulation. The company developed the iCD Design Integrity software incorporating the iCD Stackup, PDN, and CPW Planner. The software can be downloaded at icd.com.au. To read past columns or contact Olney, click here.

Solaris Acquires Jetbrain to Aid in Using Robots to Fight COVID

Solaris Disinfection Inc., a leader in IoT-connected service robotics, whose flagship Lytbot automated disinfection system is currently being used by hospitals across North America in the battle against COVID-19, announces the acquisition of Jetbrain Robotics, an innovator in hospital logistics and patient experience using autonomous mobile robotics (AMR). Invested in and supported by world-class investors Brinc & Artesian Venture Partners (AVP), Jetbrain's technology improves operational workflows in complex healthcare environments, providing quantifiable efficiencies and patient experience improvements.

Since 2017, Solaris has conducted research on the effectiveness of its pulsed UV technology against communicable human respiratory viruses like novel coronaviruses (COVID-19). "COVID has accelerated robotics deployment by five years," said Adam Steinhoff, Co-Founder, and CEO, Solaris. "In continuing our mission to improve the safety of patients and support healthcare workers, we identified Jetbrain's technology as an opportunity to improve upon our core products while providing safety, accountability and compliance-based platform technologies that help our customers effectively utilize resources and improve workflows."

Adds Val Ramanand, co-founder and executive chairman, Solaris, "At Solaris we are very proud of the growing impact we make on a daily basis in the healthcare industry by delivering practical and approachable products, designed to improve patient outcomes and healthcare operations. The acquisition of Jetbrain supports our continued mission to improve care, keep spaces safe, and ultimately help save lives in healthcare facilities globally."

Jetbrain products include delivery robots that feature a secure and traceable chain of custody for medicines and blood products, as well as patient experience robots that provide anything from clinical support to wayfinding help. The addition of Jetbrain's team enhances Solaris's expertise in healthcare robotics while extending its offering from whole room disinfection to automated delivery, logistics, and ultimately patient experience, thus delivering industry's first ecosystem approach to healthcare robotics.

(Source: PR Newswire)