May 2013
Volume 119
Issue 1925
£5.10

Electronics WORLD

THE ESSENTIAL ELECTRONICS ENGINEERING MAGAZINE
www.electronicsworld.co.uk

Mouser Audio Applications Site Inspires Guitar Audio Revamp

MOUSER ELECTRONICS.

Technology
SpaceTop3D allows users to reach inside the computer

From China
Creating a realistic virtual hand for head-mounted displays

Products
Testers, LED driver ICs, connectors and much more

TRAVELLING AT THE SPEED OF LIGHT

MALCOLM DAVIDSON, SYSTEM AND SOFTWARE QUALITY ASSURANCE CONSULTANT TO THE OFFSHORE OIL INDUSTRY, CHALLENGES CONVENTIONAL WISDOM OF WAVE PROPAGATION, WHICH HE CALLS "THE 100-YEAR MISUNDERSTANDING"

Physicists and engineers pride themselves on developing equations and models which they perceive are an accurate representation of reality and the physical world. While these equations will be logically consistent with the paradigm they were developed in, mapping them to the physical world can indicate flaws with the model itself.

In an ideal world research builds on prior knowledge and refines the models and understanding accordingly. Sometimes however, equations and models become stuck in the past and, despite new understanding, retain their place in the pantheon of science and academia. Maxwell's equations are one such example.

Questioning the Established Wisdom

It is well known – and accepted – by physicists and electronic engineers alike that all electrical energy travels at the speed of light for the medium it is in. In vacuum or air this would be 3×10^8 m/s. Therefore, whether the signal is a sine wave, a complex wave or a step function, the energy will always be moving at the defined speed of light.

This article will show, by considering only the physical constraints of travelling at the speed of light, that it is impossible for any electric field or magnetic field associated with the signal to cause the other. Maxwell's equations require faster than the speed of light travel if the conventional interpretation is valid.

Consider a sine wave in Figure 1. This signal is propagating in the medium at the speed of light. The medium could be a twisted pair cable, coaxial cable or air. Each part of this signal is moving at the same speed, and the speed of light is defined as $c = 1/\sqrt{\varepsilon_0 \mu_0}$.

If we focus on a minute "sliver" of this propagating signal, the medium and signal will be identical for any other part of the propagating wave. The fact that the original signal was a sine wave is irrelevant, for each part of the moving energy knows nothing about any other part of the signal. It only knows about itself, and it only knows about now. We may consider this sine wave signal as consisting of an infinite number of slivers adjacent to each other, all with a slightly different amplitude. Analyze a single element and the complete waveform will behave the same way. A sliver is shown in Figure 2. The sine wave is made up of "slivers" of differing amplitudes which repeat in a periodic manner, as seen by an observer, whereas a step function would be made up of "slivers" all with the same amplitude, as seen in Figure 3.

The sample signal has two properties associated with it, namely an E field and an H field, in a ratio defined by the characteristic impedance for the space travelling:

$$Z_o = \frac{E}{H} = \mu_o C_o = \sqrt{\frac{\mu_o}{\varepsilon_o}}$$

This fundamental electrical energy flow is commonly known as the Poynting Vector with the E and H fields at right angles to the direction of flow. It has been shown that a single potential measured in an open circuit, or a fully charged capacitor with steady state voltage (no magnetic field) has the same energy flow moving in opposite directions, hence cancelling out the H field.

As the energy moves through the medium, each segment of the signal knows only about itself, for it is travelling at the speed of light. There can be no 'a priori' knowledge about what is, either ahead of it, or what is behind it. If there were information it would have to travel faster than the speed of light, which has been shown to be impossible.

Each part of a signal is just moving through a medium. If it is a step, then all values of E, the electric field and H the magnetic field will be identical after the initial transition. As mentioned earlier, there is no knowledge inherent within the signal of what it is composed of, however an observer may 'see' it as a step function, a pulse or a sine wave. Each of these observations will be taken at one point in time as the signal passes by.

The key awareness to take away from this is that there is only a "Now" for energy; in any

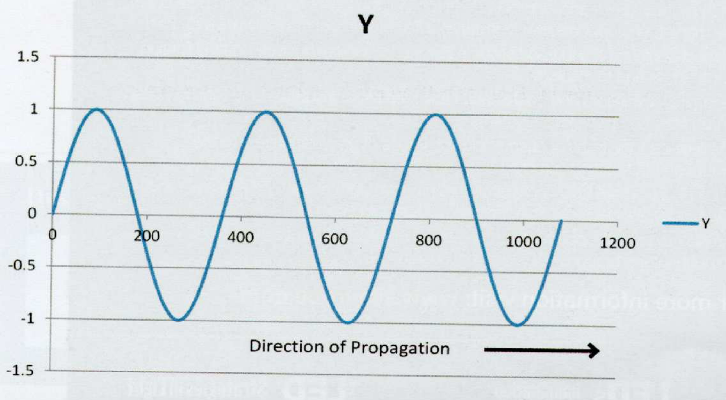

Figure 1: Conventional sinusoidal wave

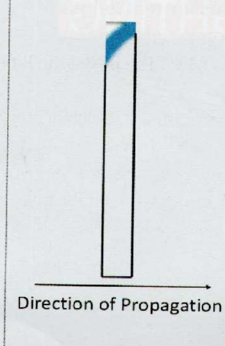

Figure 2: Small segment or sliver of a sine wave

Figure 3: A digital step, typical of any binary signal

instant there is no causality within the signal itself, merely a constant relationship between the E and H components.

This concept will now be considered when we look at some of the most fundamental and key equations developed more than 100 years ago.

Basic Equations Considered

Maxwell's equations, in their differential form can be expressed as:

$$\nabla \cdot E = \rho$$

$$\nabla \cdot B = 0$$

$$\nabla \times E + \frac{\partial B}{\partial t} = 0$$

$$\nabla \times B = J + \frac{\partial B}{\partial t}$$

Let's consider there can be no causality within a signal of any kind. Each equation will be reviewed from the perspective of this "sliver" of energy, having an E & H field moving at the speed of light for the medium. (We assume a constant Zo, which is the characteristic impedance that will result in a constant non-varying speed and, hence, no internal discontinuities.)

The electric field is:

$$\nabla \cdot E = \rho$$

otherwise known as Gauss's Law: "Gauss's Law for the electric field states that the electric flux through any closed surface is proportional to the amount of electric charge contained within that surface."

The sliver can be viewed as a single location in space. We reverse the definition and state that: "The charge measured at any point in space is equal to the total electric field observed at that location".

The magnetic field is:

$$\nabla \cdot B = 0$$

otherwise known as Gauss's Magnetism Law: "The flux of the B field through a closed surface is zero".

There is no such thing as a magnetic monopole. The magnetic field can be seen as concentric rings at right angles to the direction of motion. If there is an H field travelling along a transmission line, then it is bounded by equal and opposite currents flowing in the guide wires. If we now look at the E and H fields moving along a transmission line they would look like those in Figure 4.

The varying electric field is:

$$\nabla \times E + \frac{\partial B}{\partial t} = 0$$

This infers that a changing electric field causes a changing magnetic field. The varying magnetic field is:

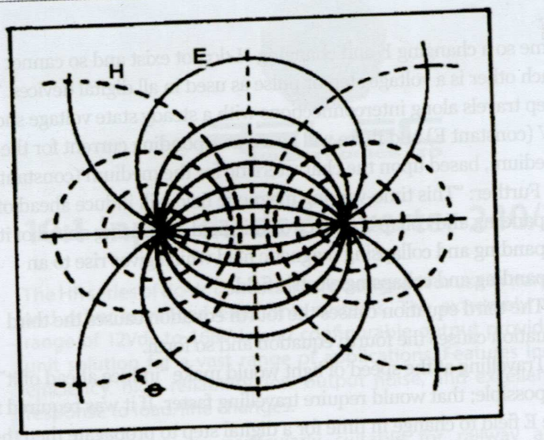

Figure 4: E and H fields are defined by the characteristic impedance of the medium

$$\nabla \times B = J + \frac{\partial B}{\partial t}$$

This also infers that a changing magnetic field causes a changing electric field. (The J term was added to cope with the observed current passing through a capacitor when the electric field was changing.)

There are many similar references to these equations stating such concepts as: "A flow of electric current will produce a magnetic field. If the current flow varies with time (as in any wave or periodic signal), the magnetic field will also give rise to an electric field. Maxwell's equations show that separated charge (positive and negative) gives rise to an electric field, and if this is varying in time as well it will give rise to a propagating electric field, further giving rise to a propagating magnetic field." [2]

Or let's consider how radio waves propagate. At the transmitter, we generate an alternating electric charge (that is an AC voltage), which we apply to a wire (the transmit antenna). A time-varying electrostatic field now surrounds the wire, in accordance with Maxwell's first equation. As the electrostatic field expands and collapses, it induces in front of it an expanding and collapsing magnetic field, the shape of which is described by Maxwell's fourth equation. This time-varying magnetic field will induce ahead of it an expanding and collapsing electrostatic field, as described by Maxwell's third equation. And so the wave propagation: expanding and collapsing electrostatic field, inducing ahead of it an expanding and collapsing magnetic field, which gives rise to an expanding and collapsing electrostatic field. Maxwell's third equation, fourth equation, third equation and so forth, until the wave reaches its destination. [3]

This is typical of many references to the physical implications of Maxwell's equations. However, when we realize that each "sliver" of any time-varying field has both an E field and an H field component that is unchanging at that instant in time and location in space, it is impossible for a time-varying field to induce anything.

The signal propagating from an antenna contains a signal which has two components (E and H) they are related by the characteristic of free space which is 120 x pi, approximately 376 ohms. The speed of this waveform in space is 3 x 10^8m/s. Each slightly different amplitude of the E field has a corresponding H field.

As this signal moves through space at the speed of light each "element" knows nothing about its neighbour, for it is travelling at the speed of light; it cannot "see" ahead of itself and it cannot "know" about the past – in the same way that we only know about this moment in time, the now.

One good example of a propagating wave which does not vary in time so a changing E and changing H do not exist and so cannot cause each other is a voltage step or pulse as used in all digital devices. The step travels along interconnections with a steady state voltage such as 5V (constant E) and there will be a corresponding current for the medium, based upon the characteristic for the medium (constant H).

Further: "This time-varying magnetic field will induce ahead of it an expanding and collapsing electrostatic field... inducing ahead of it an expanding and collapsing magnetic field which gives rise to an expanding and collapsing electric field..."

The third equation causes the fourth equation causes the third equation causes the fourth equation and so forth.

Travelling at the speed of light would make "induce ahead of it" impossible; that would require travelling faster. If it was required for the E field to change in time for a digital step to propagate then the signal would not move (maybe the leading edge and trailing edge only). We have 70-plus years of knowing that this is a false notion and the step with a steady voltage and current does travel at the speed of light for the medium.

Charging a Capacitor

Consider a step function injected into a parallel-plate capacitor via a long cable such as a coax or a twisted pair. Each component can be viewed as a transmission line with particular characteristics. We are only interested in the characteristic impedance Z_0 of each. In this case:

Z_0 – coax = 75 ohms
Z_0 – capacitor = 0.5 ohms

$$Zo = \sqrt{\frac{L}{C}}$$

The equation above shows that Z_0 is the square root of inductance per unit length divided by capacitance per unit length. If C is large, then Z_0 becomes small, hence the value of 0.5 ohms. This appears as nearly a short circuit to an applied voltage step, hence most of the signal is reflected back towards the source. However, a small voltage propagates along the parallel plates of the capacitor and upon reaching the end of them "sees" an open circuit. This reflects back on the incoming energy, doubling the value observed at the open-circuit end.

When this front edge reaches the discontinuity between the capacitor and the coaxial cable, there will be another reflection.

$$\text{The Reflection Coefficient} = \frac{R_l - Z_0}{R_l + Z_0} = \frac{75 - 0.5}{75 + 0.5} = 0.986$$

Nearly all of the signal is reflected back into the capacitor, with a slightly smaller amplitude. After many reflections there is a balance between the energy flowing from the left and the right. Figure 5 shows the incremental build-up of charge using the distributed model. [4]

The H or magnetic field has been cancelled out finally, so there is no current flow observed. The capacitor is said to be fully charged. However, note that the energy continues to flow. The TEM wave is propagating in both directions within the capacitor. When we now apply a sinusoidal time-varying field to a capacitor, the energy propagating into the device is constantly changing, so the reflected signal will always be different to the applied signal. This is because the capacitor is distributed in space (has dimension). Subsequently, the H fields will not cancel and thus an electric current will be measured. This is known as "displacement current" and is merely the difference between the Poynting Vector signals moving in opposite direction.

We always consider the sine wave to be made up of sequential slivers of energy with differing amplitudes. Therefore, the physical concepts outlined here apply to all kinds of waves.

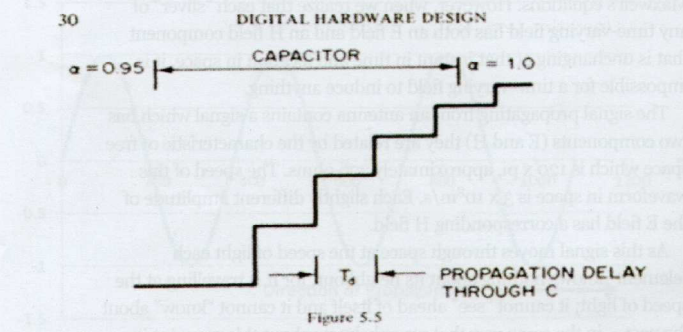

Figure 5: Flux of the electric field through a closed surface is due to the charge density enclosed

Process of Integrating New Information

As a society we generally believe that current theories have built upon the ideas of the past, refined them, added to them and filtered out those which no longer apply. For example, Sir William Preece, Head of the British Post Office in the early 1900s thought the correct model for a transmission line was a lumped RC model (resistance and capacitance). Oliver Heaviside argued that the model must include L, inductance. Heaviside's model was more accurate, despite many protestations to the contrary. The LCR model became part of the accepted scientific truth and integrated into conventional theories.

Now, with the advent of much faster electronic systems, we have to continue to be open to new models and more accurate equations for non-lumped components. The reliable functioning of these devices relies upon appropriate equations and models.

How does industry, or indeed academia deal with change, cope with modifying their world view in light of new information, new demands of reality? Ultimately, as physicists, scientists or engineers we must seek the truth. Why be an instrumentalist and settle for conventional wisdom? As physicists are pushing the boundaries of knowledge daily in the pursuit of the origins of the universe, we must do likewise within the domain of electrical energy propagation.

Any equation or model which requires a mindset which disobeys one of the basic laws of nature, by definition, cannot be accurate, regardless of its history or perceived importance. The process of acquiring and integrating new information may demand that we close one door on a widely accepted model, but this will afford us the opportunity to open up another door. With courage we can step into this new world and forge new equations and new models which adhere to the natural world and not to the dusty tomes of the past. ●

REFERENCES

[1] Maxwell's differential equations simplified for waves in free space. See reference: http://www.setileague.org/articles/ham/maxwell.pdf
[2] http://maxwells-equations.com/index.php
[3] "Maxwell without Tears" by H. Paul Shuch Penn College of Technology. http://www.setileague.org/articles/ ham/maxwell.pdf
[4] Reference: Digital Hardware Design Catt Walton Davidson 1979 Macmillan Press