Displacement Current: The Key to Electromagnetic Energy Propagation

Beyond Design

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The propagation of electromagnetic energy can be controlled in several ways depending on the medium the energy is traveling in. However, electromagnetic waves do not require a medium to propagate. This means that electromagnetic waves can travel not only through liquids, solids, and air, but also through the vacuum of space. What's more, they do not require electron current flow for the transfer of energy.

Electromagnetic energy can be guided in the following ways:

1. **Direct Current:** Conductors guide the energy flow.
2. **Alternating Current:** Conductors, coplanar and substrate integrated waveguides at high frequencies control the energy.
3. **Radio and Microwave Frequencies:** Waveguides and antennae guide the energy.
4. **Light Frequency:** Optical fiber channels, lenses/mirrors, and gravitational lensing control the energy path.

Continuing on from my previous column, "Forget What You Were Taught," let's take a closer look at how electromagnetic energy propagates at different frequencies[1].

Waveguides

A waveguide is a form of transmission line used to connect microwave transmitters and receivers to their antennas. They are metal tubes made of high-quality copper and brass. A waveguide can have a rectangular, circular, or elliptical cross-section. The rectangular section is most used for relatively short connections. Figure 1 depicts a plot in QWED software of the electric and magnetic field distribution along a rectangular waveguide. A transverse electromagnetic wave travels perpendicular to both the electric and magnetic fields.

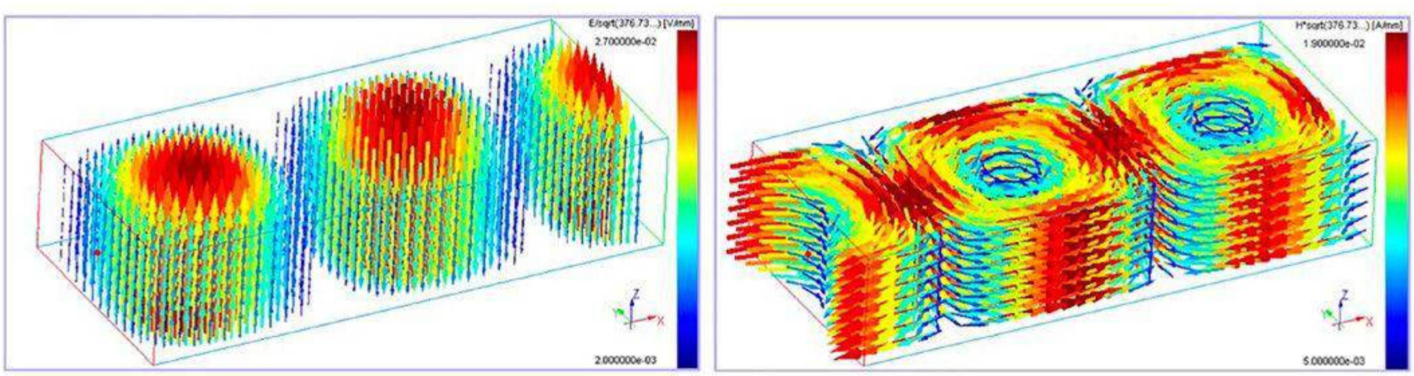

Figure 1: Electric field (left) and magnetic field (right) distribution along a rectangular waveguide. (Source: QWED)

Electric and magnetic fields, which are used for the transport of energy, are equal to zero on the metal surface of the waveguide. Therefore, these fields are confined to the waveguide's internal space, which minimizes losses. Without the physical constraint of a waveguide, wave intensities decrease according to the inverse square law as they expand uniformly in all directions. Waveguides act like conduits for high frequency displacement currents. All transmission lines function as conduits of electromagnetic energy when transporting pulses or high frequency waves.

Wireless Power

Most of us have Qi wireless chargers for our smart devices—who could live without them? The big advantage to using these chargers is that you do not have to constantly plug in cables to charge your phone. No wires—no current—but 15W of power.

Qi wireless charging uses resonant inductive coupling between the sender (the charging station) and the receiver (the mobile device) as in Figure 2. Figure 3 shows the Qi receiver coil in an iPhone 12. The two coils act as a transformer when a compatible device is placed on a charging station.

Transformers

A transformer works by electromagnetic induction (or mutual inductance). This occurs when two electrically isolated coils are in close proximity, such that one's magnetic field couples to the other. When an alternating current is applied to the primary coil, a fluctuating magnetic field is generated, which causes electromotive force in the secondary coil. This varying electric field creates displacement current in the secondary winding. Adding an iron core to the transformer improves the efficiency by directing the electromagnetic field so that it couples directly into the sec-

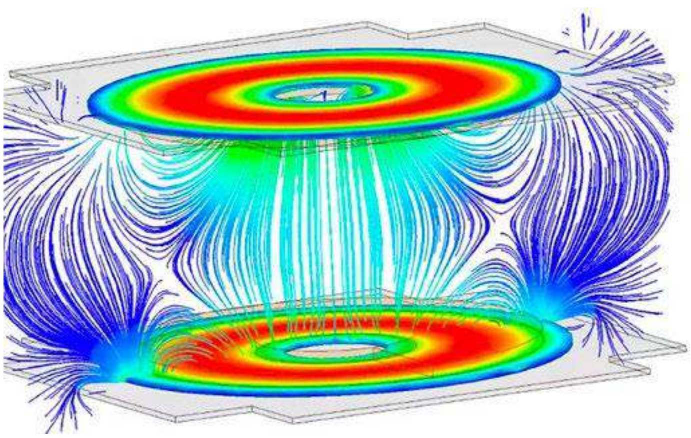

Figure 2: Qi wireless charging simulation (simulated in Ansys Maxwell).

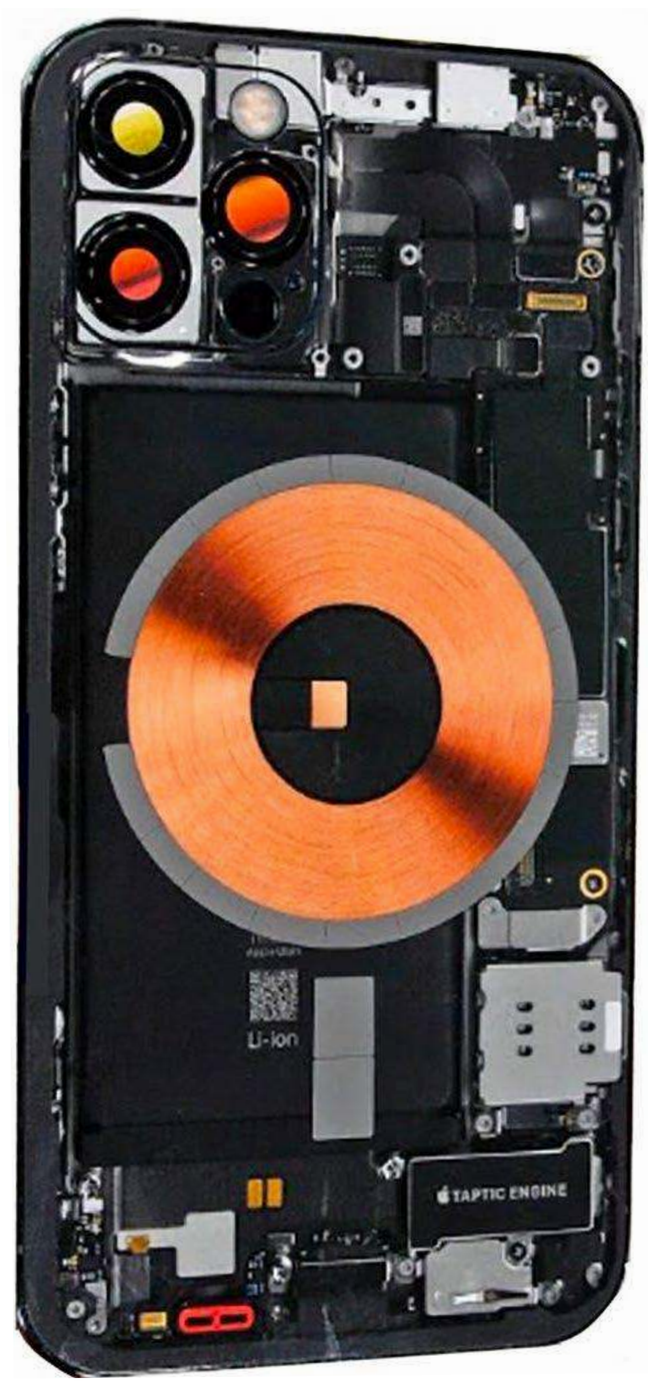

Figure 3: Apple iPhone 12.

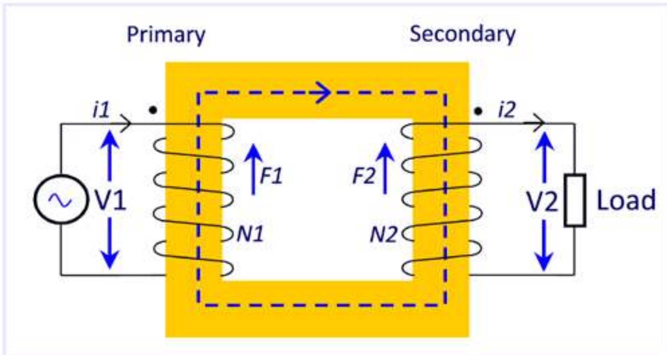

Figure 4: Basic transformer with primary and secondary coils surrounding an iron core.

ondary winding rather than radiating. Just as waveguides and traces guide electromagnetic energy, so does the core.

Transformers completely isolate the primary from the secondary. Transformers transfer the electric energy into magnetic energy (primary windings) and then back to electric energy (secondary winding). The transformer's core captures >90% of the magnetic energy and delivers it to the secondary windings.

AC Coupling of High-speed Serial Links

A capacitor is typically placed in series with both differential signals of high-speed SERDES serial links to remove common mode voltage differences between ICs or different technologies (Figure 5). Any capacitor placed in series with the signal path tends to pass the high-frequency AC portions of the signal, while simultaneously blocking the low-frequency DC portions. These capacitors are essential to a variety of high-speed interfaces. And, as the next generation of designs target data rates of 56Gbps and above, it becomes increasingly important to characterize channel transitions accurately to ensure a high confidence of success.

However, capacitors block electron flow. A capacitor in a circuit causes equal and opposite charges to appear on the plates, charging the capacitor and increasing the electric field between the plates. No actual charge is transported between its plates. Nonetheless, a magnetic field exists between the plates as though a current were present. One explanation is that displacement current flows in the dielectric and this current produces the magnetic field in the region between the plates.

This idea was conceived by James Clerk Maxwell in his 1861 paper "On Physical Lines of Force, Part III" in connection with the displacement of electric particles in a dielectric medium. Maxwell added displacement current to the electric current term in Ampère's Circuital Law. In his 1865 paper "A Dynamical Theory of the Electromagnetic Field," Maxwell used this amended version of Ampère's Circuital Law to derive the electromagnetic wave equation. This derivation integrates electricity, magnetism, and optics into one single unified theory. The displacement current term is now seen as a crucial addition that completed Maxwell's equations and is necessary to explain many phenomena, most particularly the existence of electromagnetic waves.

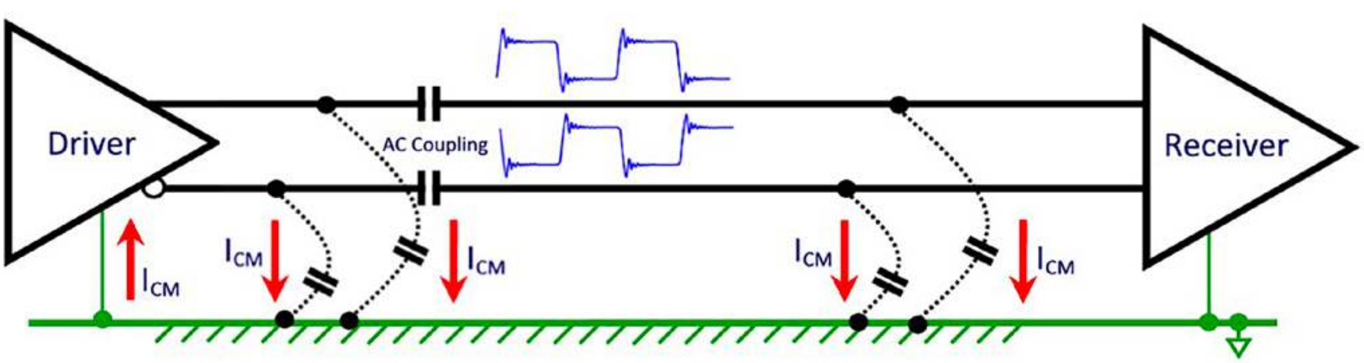

Figure 5: Common mode current (I_{CM}) is the displacement current.

Light

Maxwell described light as a propagating wave of electric and magnetic fields. More generally, he predicted the existence of electromagnetic radiation—coupled electric and magnetic fields traveling as waves at the speed of light.

Displacement current plays a vital role in the propagation of electromagnetic radiation, such as light and radio waves, through empty space. A traveling, varying magnetic field is associated with a periodically changing electric field that may be conceived in terms of a displacement current. Maxwell's insight on displacement current, therefore, made it possible to understand electromagnetic waves as being propagated through space completely detached from electric currents in conductors.

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The displacement current density term, appearing in Maxwell's equations, is the quantity $\partial D/\partial t$ that is defined in terms of the rate of change of D, the electric displacement field. Displacement current density has the same units as electric current density, and it is a source of the magnetic field just as the actual current is. However, it is not an electric current of moving charges, but rather a time-varying electric field. This implies that a changing electric field creates a magnetic field, even with no charged particles in motion. In physical materials (as opposed to vacuum), there is also a contribution from the slight motion of charges bound in atoms, called dielectric polarization.

Displacement current explains how electromagnetic energy propagates but is really just a fudge. Scientists have a creative way of accounting for what they do not comprehend: They add a constant. For instance, astrophysicists cannot explain why the universe is expanding when it logically should be contracting due to the attraction of gravity. They then created "dark energy" to account for the force of expansion. Displacement current is just another "unexplained phenomenon" that accounts for current. Few theories in physics have caused as much confusion and misunderstanding as that of displacement current.

There are two types of current:

1. ***Conduction current*** is the net flow of charges at DC. This is what we traditionally think of as current flow.
2. ***Displacement current*** is the rate of change of the electric displacement field. It is not electron current flow but rather a time-varying electric field that creates a magnetic field along a transmission line mimicking current flow.

Transmission Lines

Dan Beeker stated that: "Field energy moving through a space is the current flow in a transmission line. The magic here is the displacement current flowing through the dielectric at the wave-front, along the transmission line. Fields do all the work. Current flow is a measure of moving field energy through a space. Current flow occurs in the space between the conductors that bound the dielectric[2]."

Ralph Morrison summed it up beautifully: "Light energy can be directed by lenses; radar energy can be directed by waveguides and the energy at power frequencies can be directed by copper conductors. Thus, we direct energy flow at different frequencies by using different materials. We have learned how to control where we want the field energy to go.

"The Laws of Physics apply to everything in the universe. If we accept the concept that electromagnetic fields carry energy in space, it must be true at all frequencies in all media. That is the law. If it is true for light, it must also be true for high-speed transmission lines, 60 Hz power, and at DC[3]."

Key Points

- The propagation of electromagnetic energy can be controlled in a number of ways depending on the medium the energy is traveling in.
- The propagation of electromagnetic energy does not require electron current flow for the transfer of energy.
- Waveguides act like conduits for high frequency displacement currents.
- Transformers transfer the electric energy into magnetic energy (primary windings) and then back to electric energy (secondary winding).
- Capacitors block electron flow. However, displacement current flows in the dielectric and this current produces the magnetic field in the region between the plates.
- The displacement current term is now seen as a crucial addition that completed Maxwell's equations and is necessary to explain many phenomena, most particularly the existence of electromagnetic waves.
- Displacement current plays a vital role in the propagation of electromagnetic radiation.
- A traveling, varying magnetic field is associated with a periodically changing electric field that may be conceived in terms of a displacement current.
- Electromagnetic waves are propagated through space completely detached from electric currents in conductors.
- Displacement current is not an electric current of moving charges, but rather a time-varying electric field.
- There are two types of current: Conduction current and displacement current.
- Field energy moving through a space is the current flow in a transmission line. The magic here is the displacement current flowing through the dielectric at the wave-front, along the transmission line.
- The laws of physics apply to everything in the universe. **DESIGN007**

References

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Resources

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