

LIKE MOST EEs, YOU PROBABLY WISH YOU HAD A BETTER UNDERSTANDING OF ELECTROMAGNETIC FIELDS AND WAVES. MAYBE THE COMPLEX MATH KEEPS YOU FROM DELVING MORE DEEPLY INTO THE SUBJECT. THIS INTUITIVE TREATMENT GOES LIGHT ON MATH. IN SO DOING, IT BRINGS LIFE TO A TOPIC THAT MANY FIND DRY AND CONFUSING.

Understanding electromagnetic fields and antenna radiation takes (almost) no math

UNDERSTANDING ANTENNAS and electromagnetic fields is obviously important in RF engineering, in which capturing and propagating waves are primary objectives. An understanding of RF fields is also important for dealing with the electromagnetic-compatibility (EMC) aspects of every electronic product, including digital systems. EMC design is concerned with preventing circuits from producing inadvertent electromagnetic radiation and stray electromagnetic fields. EMC also involves preventing circuits from misbehaving as a result of ambient radio waves and fields. With digital systems' ever-increasing frequencies and edge rates, EMC is becoming harder to achieve and is no longer a topic just for experts. The seemingly mystical processes by which circuits radiate energy are actually quite simple. To understand them, you don't even need to know Maxwell's equations.

Consider the following fictitious disagreement. An electrical engineer is telling a lawyer friend about a new home-electronics project. The engineer lives near some high-voltage power lines and is working on a device for harnessing the power of the 60-Hz electromagnetic field that permeates his property. The lawyer immediately states that what the engineer plans to do would, in effect, be stealing from the utility company.

This statement angers the engineer, who replies, "That's the trouble with you lawyers. You de-

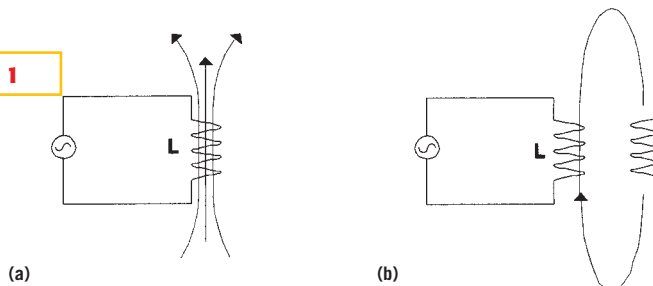
fend laws without regard to the truth. Even without my device, the stray electromagnetic energy from the power lines is radiated away and lost, so I might as well use it." The lawyer stands his ground and says that the engineer will still be stealing.

Who is right? The lawyer is correct, even though he probably doesn't know the difference between reactive and radiating electromagnetic fields. The field surrounding the power lines is a reactive field, meaning that it stores energy as opposed to radiating energy, so the engineer's device would in fact be "stealing" energy from the power lines. But why? Why do some circuits produce fields that only store energy, whereas others produce fields that radiate it?

THE ENERGY GOES BACK AND FORTH

To further examine this situation, consider the circuit of **Figure 1a**. It is a simple circuit consisting of an ac power source driving an inductor. If the inductor is ideal, no energy is lost from the power sup-

Figure 1



An inductor creates a reactive field that stores energy (a). Adding a second inductor harnesses the reactive field to transfer energy to a load without metallic contact (b).

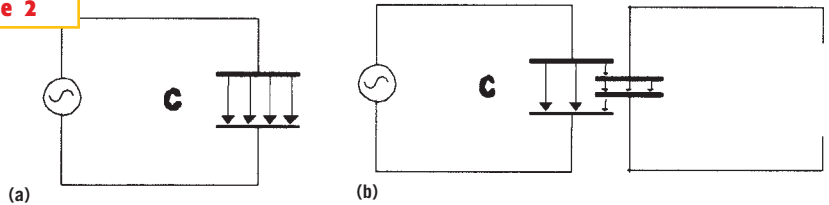
ply. The inductor does, however, produce an electromagnetic field. Because no energy is lost, this field is purely a storage field. The circuit pumps power into the field, which then returns energy to the circuit. Because of this energy cycling, the current and voltage of the inductor are out of phase by 90° , thus producing a reactive impedance, $Z_L = j\omega L$. The reactive nature of the impedance explains why such storage fields are called reactive fields.

Referring to **Figure 1b**, when you place a second circuit consisting of an inductor and a resistor near the first circuit, the field from L_1 couples to L_2 and causes current to flow in the resistor. (The coupled fields create a transformer.) The reactive field transfers energy from the source to the resistor even though the original circuit has not changed. This action suggests that a reactive field can store or transfer energy, depending upon what other electrical or magnetic devices are in the field. So the reactive field “reacts” with devices that are within it. Similarly, a capacitor creates a reactive field that can store energy, transfer energy, or do both (**Figure 2**).

Now consider the circuits of **Figure 3**. An ac voltage source drives two types of ideal antennas, a half-wavelength loop and a half-wavelength dipole. Unlike the previous circuits, the antennas launch propagating fields that continuously carry energy away from the source. The energy is not stored but propagates from the source regardless of whether there is a receiving antenna. This energy loss appears as resistance to the source in a similar manner to how loss in a resistor corresponds to heat loss.

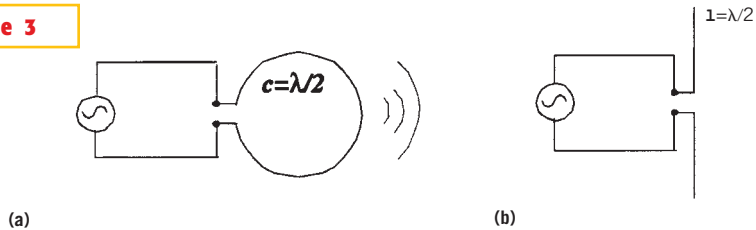
Now back to the engineer and the lawyer. The engineer thought that the power-transmission line near his house was radiating energy the way an antenna

Figure 2



A capacitor creates a reactive field that stores energy (a). Adding a second capacitor harnesses some of the reactive field to transfer energy to a load without metallic contact (b).

Figure 3



The two most basic antennas are a loop antenna whose circumference is equal to the source wavelength divided by 2 (a) and a dipole antenna whose length is equal to the source wavelength divided by 2 (b).

does and that he was just collecting the radiating energy with a receiving antenna. However, when the engineer measured the field on his property, he measured the reactive field surrounding the power lines. When he activates his invention, he is coupling to the reactive field and removing energy that is stored in the field surrounding the power lines—energy that would otherwise be cycled to the loads. The circuit is analogous to the transformer circuit in **Figure 1b**, so the engineer is, in fact, stealing the power.

These examples illuminate the characteristics of reactive and radiating electromagnetic fields, but they still do not answer the question of why or how radiation occurs. To understand radiation, it is best to start with the analysis of the field of a point charge.

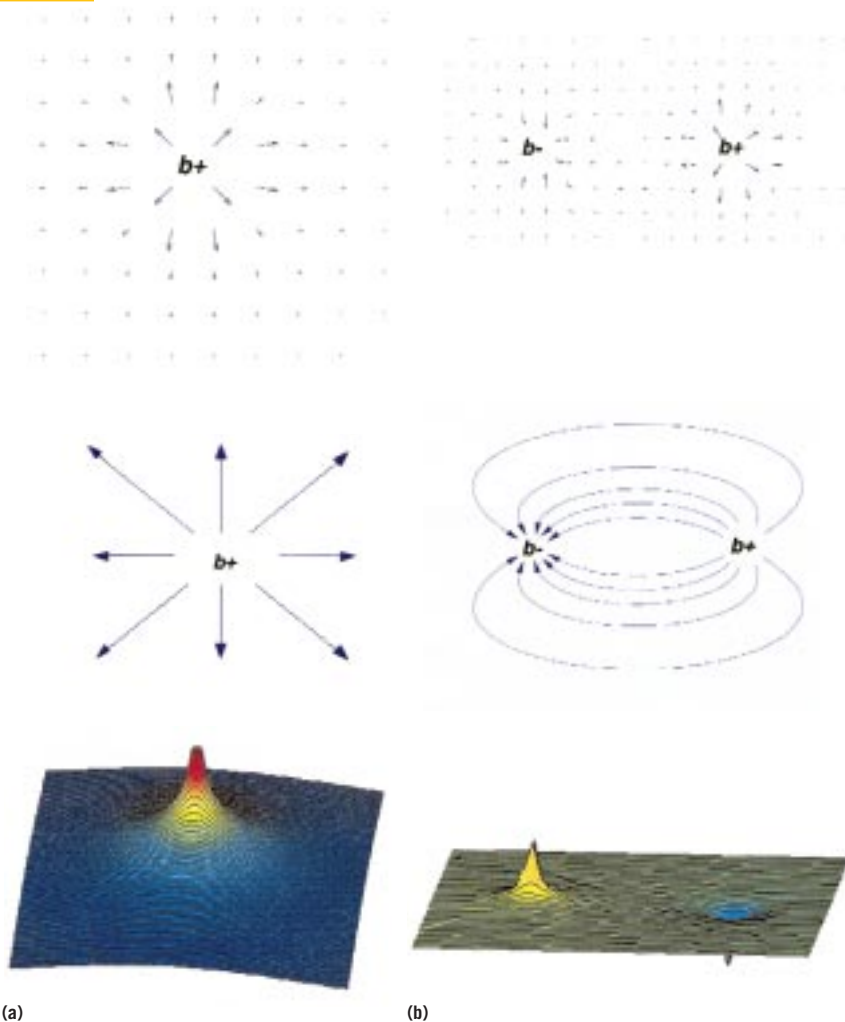
For a single charged particle, such as an electron, the electric field forms a simple radial pattern (**Figure 4**). By convention, the field lines point outward for a positive (+) charge and inward for a negative (−) charge. The field remains the same over time; hence, it is called a static field. The field stores the particle’s electromagnetic energy. When another charge is present, the field imparts a force on the other object, and energy is transferred. When no other charged particles are present, the field has no effect but to store energy. The fact that energy is transferred from the field only when another charged particle is present is a defining characteristic of the static field. As you will soon learn, this fact does not hold true for a radiating field.

Now consider the same charged par-

TABLE 1—SUMMARY OF FIELD CHARACTERISTICS

| | Near (reactive) field | Far (radiated) field |
|------------------|------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Carrier of force | Virtual photon | Photon |
| Energy | Stores energy; can transfer energy via inductive or capacitive coupling | Propagates (radiates) energy |
| Longevity | Extinguishes when source power is turned off. | Propagates until absorbed |
| Interaction | Act of measuring field or receiving power from field causes changes in voltages/currents in source circuit | Act of measuring field or receiving power from field has no effect on source |
| Shape of field | Depends completely on source circuit | Spherical waves; at far distances, field takes shape of plane waves |
| Wave impedance | Depends on source circuit and medium | Depends solely on propagation medium |

Figure 4



You can show the electric field of a static charge (a) or a dipole (b) as a vector plot, a streamline plot, and a log-magnitude contour plot.

ticle moving at a constant velocity, much lower than the speed of light. The particle carries the field wherever it goes, and, at any instant, the field appears the same as in the static case (Figure 5a). In addition, because the charge is now moving, a magnetic field also surrounds the charge in a cylindrical manner, as governed by Lorentz's law. This magnetic field is a consequence of the fact that a moving electric field produces a magnetic field and vice versa. As with a static charge, both the electric and magnetic fields of a constant-velocity charge store energy and transmit electric and magnetic forces only when other charges are present. To make the description eas-

ier, the rest of this article ignores the magnetic field.

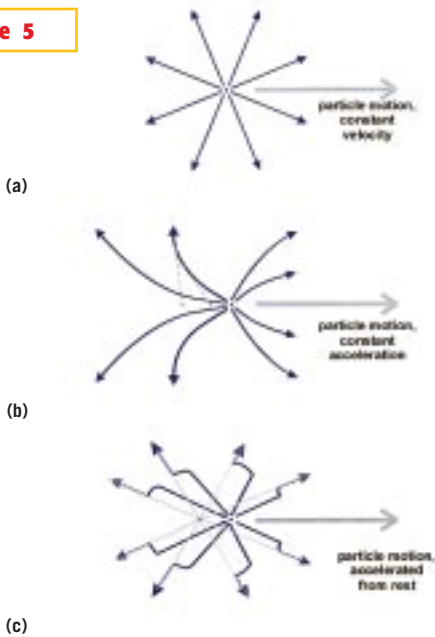
When a charged particle accelerates, the lines of the electric field start to bend (Figure 5b). A review of Einstein's theory of relativity helps to explain why the bending occurs: No particle, energy, or information can travel faster than the speed of light, c . This speed limit holds for fields as well as particles. For that matter, a field is just a group of virtual particles (see sidebar "Quantum physics and virtual photons"). For instance, if a charged particle were suddenly created, its field would not instantly appear everywhere. The field would first appear immediately around the particle and then

extend outward at the speed of light. For example, light takes about eight minutes to travel from the sun to earth. If the sun were to suddenly extinguish, people on earth would not know until eight minutes later. Similarly, as a particle moves, the surrounding field continually updates to its new position, but this information can propagate only at the speed of light. Points in the space surrounding the particle actually experience the field corresponding to where the particle used to be. This delay is known as *time retardation*. It seems reasonable to assume that even a charge moving at constant velocity should cause the field lines to bend because of time retardation. However, nature (that is, the electromagnetic field) gets around the delay by predicting where the particle will be based on its past velocity. Therefore, field lines of particles moving at constant velocities do not bend. This behavior stems from Einstein's theory of special relativity, which states that velocity is a relative—not an absolute—measurement. Furthermore, the bent field lines of the charge correspond to radiating energy. Therefore, if the field lines are straight in one observer's reference frame, conservation of energy requires that all other observers perceive them as straight.

A CURIOUS KINK

To understand why the bent field lines of a charge correspond to radiated energy, consider a charged particle that starts at rest and is "kicked" into motion by an impulsive force. When the particle accelerates, a kink appears in the field immediately surrounding the particle. This kink propagates away from the charge, updating the rest of the field that has lagged behind (Figure 5c). Part of the energy exerted by the driving force is expended to propagate the kink in the field. Therefore, the kink carries with it energy that is electromagnetic radiation. Fourier analysis shows that because the kink is a transient, it consists of a superposition of many frequencies. Therefore, a charge accelerating in this manner si-

Figure 5



The electric field follows a particle moving to the right with constant velocity (a); the electric field follows a particle moving to the right with constant acceleration (b); the electric field follows a particle coming into motion from a resting condition (c). Particle locations and field lines at earlier times appear in gray.

multaneously radiates energy at many frequencies.

You can also analyze this phenomenon from a kinetic-energy perspective. In freshman physics, you learned that it takes a force to accelerate a particle and that the force transfers energy to the particle, thus increasing its kinetic energy. The same analysis holds true for the particle's field. Energy is required to accelerate the field. This energy propagates outward as a wave, increasing the field's kinetic energy (Figure 6a).

All electromagnetic radiation—be it RF, thermal, or optical—is created by changing the energy of electrons or other charged particles. This general statement applies not only to free-electron-energy changes that result from acceleration and de-

celeration, but also to quantum-energy-state (orbital) changes of electrons bound into atoms.

THE FIELD OF AN OSCILLATING CHARGE

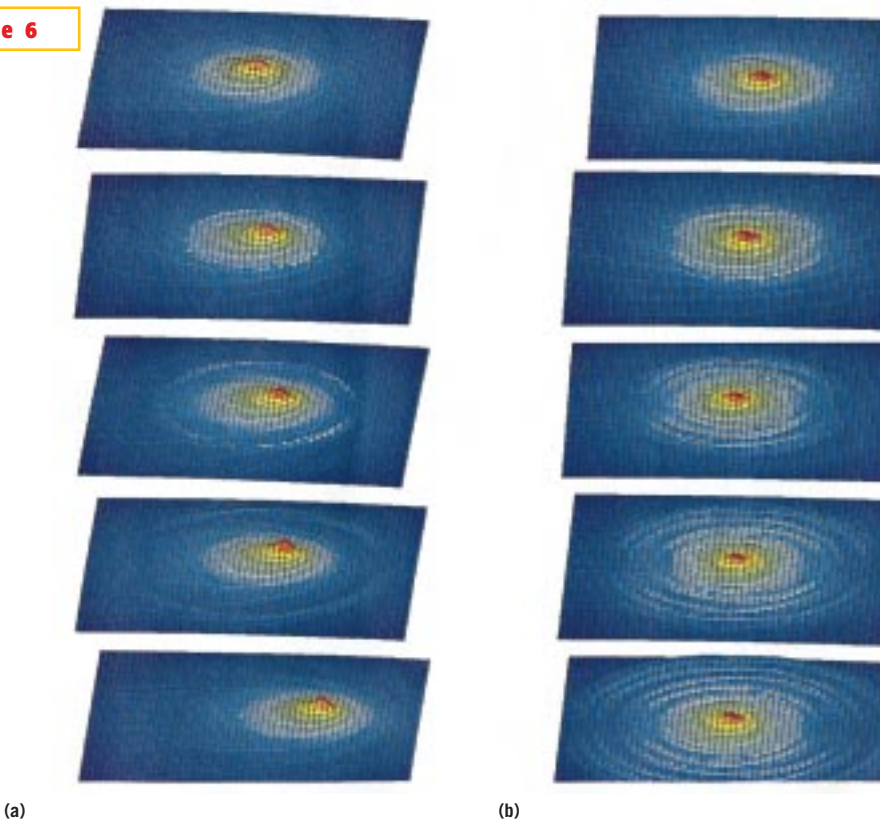
A charge moving in a circle experiences a sinusoidal acceleration. In fact, sinusoidal acceleration occurs for a charge moving in any oscillatory manner. In this case, the “kinks” in the field are continuously varying and sinusoidal, and the electromagnetic radiation occurs only at the frequency of oscillation. An oscillating charge produces rippling waves that propagate outward, in some ways similar to the waves produced when you toss a pebble into a pond (Figure 6b).

If you connect a constant voltage across a length of wire, the voltage causes a proportional current governed by Ohm's law ($I=V/R$). The dc current traveling in a wire consists of migrating electrons. Although the path of each individual electron is random and complex, the average movement of the electrons, considered as a group, causes a constant drift of charge. Therefore, at a macroscopic level, you can ignore the specifics of each electron and model the

current as a fictitious charge traveling at a constant velocity. Radiation does not occur because the effective charge travels at a constant velocity and experiences no acceleration. (Collisions at the atomic level cause randomness in the electron movement. This random component of motion produces thermal radiation and electrical noise, which are not germane to this discussion.)

If the voltage across a wire slowly oscillates in time at frequency f_0 , the accompanying electric field takes the same form as that of the dc

Figure 6



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 These log-magnitude plots show the electric field of accelerated charges. A charge starts at rest and is accelerated by a short impulsive force (a). A charge starts at rest and is sinusoidally accelerated along the horizontal axis (b).

charge, except that the magnitude varies between positive and negative values (Figure 8).

RADIATION FROM OSCILLATING CHARGES

Relating frequency to wavelength by $\lambda=c/f$, you can define a slow oscillation as any frequency whose corresponding wavelength is much greater than the length of the wire. This condition is often called *quasistatic*. In this case, the current in the wire varies sinusoidally, and the effective charge experiences a sinusoidal acceleration. Consequently, the oscillating charge radiates electromagnetic energy at frequency f_0 . The power (energy per time) radiated is proportional to the magnitude of current and

Figure 7



In this depiction of the electric field surrounding a wire carrying a dc current, shades of gray denote the relative voltage levels inside the wire. Magenta arrows denote the current.

the length of the wire because both parameters increase the amount of moving charge. The radiation power is also proportional to the frequency because the charge experiences a greater acceleration at higher frequencies. (Imagine yourself on a spinning ride at an amusement park. The faster it spins, the greater the acceleration you and your lunch feel.)

Expressed algebraically, Radiated power \sim current \times length \times frequency.

This expression clearly shows why RF signals radiate more readily than do lower frequency signals, such as those in the audio range. In other words, a given circuit radiates more at higher frequencies. Because wavelength is inversely proportional to frequency ($\lambda=c/f$), an equiva-

QUANTUM PHYSICS AND VIRTUAL PHOTONS

Quantum physics was born just 100 years ago. In 1900, Max Planck presented his theory on the quantization of energy levels of thermal radiation. Five years later, Albert Einstein further expanded quantum physics when he postulated that all energy is quantized. At the core of his theory was the notion that light and electromagnetic radiation in general are quantized into particles called photons. This concept points out the bizarre wave-particle duality of light. In some ways, electromagnetic radiation acts as a distributed wave of energy. In other respects, radiation acts as a localized particle.

Now what about the energy in static or reactive electromagnetic fields? Quantum physics states that any energy must consist of individual packets, or *quanta*, but this statement implies that even the static field must consist of particles. In fact, the static field does consist of particles—virtual photons. To explain virtual photons, step further into the strange world of quantum physics.

At the crux of quantum physics is the idea that all electromagnetic energy is transferred in integer quantities of a funda-

mental unit, Planck's constant. Mathematically, you can state this concept as $E=h\nu$, where E is energy, h is Planck's constant, and ν is the frequency of the photon. Another principle of quantum physics is the Heisenberg uncertainty principle. To Einstein's dismay, it was his quantum theory that led directly to the uncertainty principle, which states that all measurements have inherent uncertainty.

Einstein expressed his dislike of this uncertainty when he said, "God does not play dice," but he could never disprove the existence of uncertainty. Specifically, the uncertainty principle states that you can never know both the exact position and momentum of any particle. Mathematically, the bounds on the errors in determining position (Δx) and momentum (Δp) are related as follows: $\Delta p \Delta x \geq h/(4\pi)$.

The uncertainty principle is not a limit set by the accuracy of measuring equipment. It is a fundamental property of nature. This concept is straightforward:

To measure a particle, you must interact with it. Think about looking at small objects through a microscope. To see what you're

looking at, you shine a light source (or electron beam) on the object. Although the light beam may not have much consequence when you measure large objects, such as a baseball, it drastically changes the position, momentum, or both of tiny objects, such as electrons. The only way to get around this problem would be to reduce the power of the light source to an infinitesimal level. But Einstein's quantum theory limits how small the energy can be. To observe any object, you must transfer an amount of energy, $E=h\nu$, which alters the state of the object you are observing. Hence, the very act of measuring or interacting with a particle changes its position and or momentum. Thus, you are left with bizarre consequences that even Einstein didn't foresee.

From another point of view, the uncertainty principle states that particles of small enough energy and short enough life spans can exist, but you can never measure them. This idea is stated as: $\Delta E \Delta t \leq h/(4\pi)$.

This expression allows for "virtual particles" to spontaneously appear and disappear as long as they obey both the uncertainty

principle and the law of conservation of energy. You can never directly observe or measure these ephemeral particles, hence the term "virtual particles."

Now back to electromagnetic fields. The stored energy in an electromagnetic field allows the creation of these virtual particles. These particles carry the electromagnetic force in reactive or nonradiating fields. The particles have all of the properties of the real photons that make up radiating fields except that they are fleeting in time and can never exist unless their source is present.

An electron in free space is a good example. It is surrounded by a static electric field that stores energy. When no other charged particles are present, the virtual photons that constitute the field appear and disappear unnoticed without transferring energy. Now, if you place a second charge near the electron, the electron's virtual photons transmit a force to the charge. In a reciprocal manner, the virtual photons from the field of the charged particle transmit a force to the electron. This strange behavior is how electromagnetic force operates at the quantum level.

lent expression is: Radiated power~current×length/wavelength.

Hence, at a given source voltage and frequency, the radiated power is proportional to the length of the wire. In other words, the longer you make an antenna, the more it radiates.

Until now, the discussion has dealt only with slowly oscillating fields. When you increase the frequency of the voltage source so that the wavelength is approximately equal to or less than the length of the wire, the quasistatic picture no longer holds true. The current is no longer equal throughout the length of wire (Figure 9). In fact, the current points in different directions at different locations. These opposing currents cause destructive interference just as water waves colliding from opposite directions tend to cancel each other out. The result is that the radiation is no longer directly proportional to the wire or antenna length.

Figure 10 shows a plot of radiated power as a function of antenna length. When the antenna is smaller than a wavelength, the radiated power is roughly proportional to the length. However, for wire lengths near or above a wavelength, the radiated power relates as a slowly increasing and oscillating function. So, why is a length of $\lambda/2$ usually chosen for dipole antennas ($\lambda/4$ for a monopole)? The “diminishing returns” of the radiated power versus wire length partially explain why dipole antennas’ length is usually chosen to be less than a wavelength). The length of $\lambda/2$ is chosen because at this wavelength, the antenna is electrically resonant, which makes its electrical

impedance purely real, and the radiation pattern is simple (single-lobed) and broad.

NEAR AND FAR FIELD

As mentioned earlier, an ac circuit has a reactive field and a radiating field. The reactive field of an ac source circuit or system is often called the near field because it is concentrated near the source. Similarly, the radiating field is referred to as the far field because its effects extend far from the source. Here’s why.

You can represent the power density of an electromagnetic field at a distance, r , from the source by a series in $1/r$:

$$\text{Field power density} = P_D = C_1/r^2 + C_2/r^3 + C_3/r^4 + \dots$$

Now, imagine a sphere with radius, r , centered at the source. You can calculate the total power passing through the surface of the sphere by multiplying the power density by the sphere’s surface area:

$$\text{Total power leaving sphere} = P = (4\alpha\pi r^2)P_D = 4\pi(C_1 + C_2/r + C_3/r^2 + \dots)$$

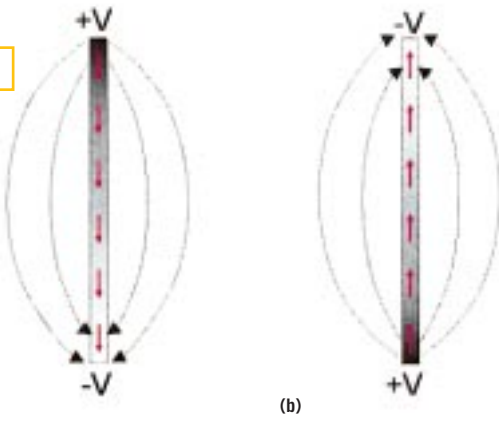
When you examine this formula, you can see that the first term is purely a constant. For this term, no matter what size you make the sphere, the same amount of power flows through it. This result is just a mathematical way of showing that power flows away from the source. Therefore, the first term is due solely to the radiated field. Also, as r gets large, all the other terms become negligible, leaving only the radiated term. Conversely, at close distances (small values of r), the nonconstant terms become much larger, and the constant radiating term be-

comes negligible. These nonconstant terms taken together represent the power in the reactive field.

The boundary between the near and far fields is generally considered to fall at about $\lambda/(2\pi)$. Furthermore, the reactive field typically becomes negligible at distances of 3 to 10λ . It is interesting to compute the boundary at different frequencies. At 60 Hz, the boundary is 833 km. Therefore, almost all cases of 60-Hz interference occur in the near (reactive) field. At 100 MHz, the boundary is 0.5m, making this frequency useful for radio communication. At 5×10^{14} Hz (optical waves), the boundary is 0.1 μm , explaining why optical sources such as light bulbs always appear as radiating sources and never as reactive sources.

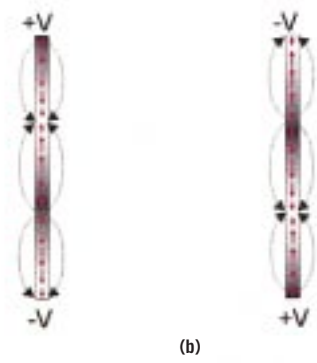
The near and far fields have other characteristics. The shape of the near field is closely related to the structure of the source, whereas the far field becomes independent of the source, taking the form of spherical waves. At large distances, the far field takes the form of traveling plane waves. The requirement for the plane-wave approximation is $r > 2(d_s + d_r)^2/\lambda$, where d_s is the size of the source antenna, d_r is the size of the receiving antenna, and r is the distance between the antennas. The wave impedance (ratio of electric- to magnetic-field magnitude) of the near field is also a function of the source circuit, whereas in the far field, the wave impedance, η , depends only on the medium ($\eta = 377\Omega$ in free space). Figure 11 graphs the wave impedance as a function of distance. Table 1 summarizes the field characteristics.

Figure 8



The electric fields surrounding a wire carry a slowly varying ac current. Magenta arrows denote the current, and shades of gray denote the relative voltage levels inside the wire at time $t=0$ (a) and at time $t=T/2$, a half-cycle later (b).

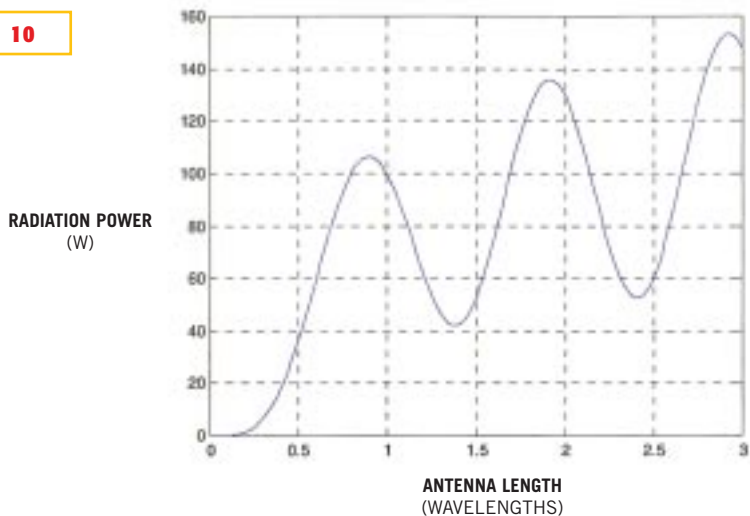
Figure 9



The electric field surrounding a wire carries a rapidly varying ac current. Magenta arrows denote the current, and shades of gray denote the relative voltage levels inside the wire at time $t=0$ (a) and at time $t=T/2$, a half-cycle later (b).

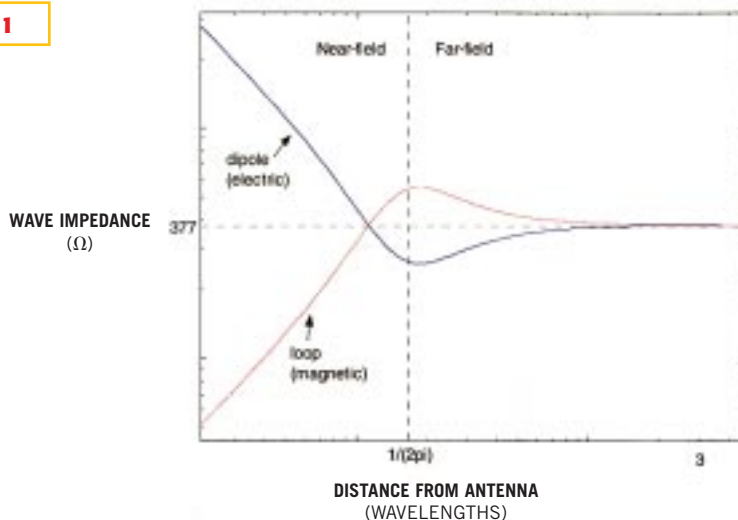
Stationary charges and charges moving with constant velocity produce reactive fields; accelerating charges produce radiating fields in addition to the reactive field. DC sources cause a constant drift of charges and hence produce reactive fields. AC sources cause the acceleration of charges and produce both reactive and radiating fields. Radiating fields carry energy away from the source regardless of whether there is a receiving circuit or antenna. In the absence of another circuit, reactive fields store energy capacitively, inductively, or both ways. In the presence of another circuit, reactive fields can transfer energy through inductive or capacitive coupling. In general, radiation increases with frequency and antenna length. Similarly, radiation and transmission-line effects are usually negligible when wires are much shorter than a wavelength. The reactive field's characteristics depend greatly on the source circuit. The radiating field's characteristics, such as wave impedance, are independent of the source. □

Figure 10



Radiated power emitted from a dipole antenna is a function of the antenna length. The source current is 1A.

Figure 11



Compare the wave impedance as a function of distance from a loop antenna (as in Figure 3a) with that of a dipole (as in Figure 3b). In the near field, the loop antenna's radiated energy is mostly magnetic. At close range, the dipole antenna's radiated energy is mostly electric. In the far field, the division between electric and magnetic energy is the same for both antenna types.

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