SECTION 2

ADVANCED PRACTICAL RADIO ENGINEERING

TECHNICAL ASSIGNMENT

RADIATION AND RADIATORS

245D

- TABLE OF CONTENTS'-

RADIATION AND RADIATORS

RADIATION AND RADIATORS

GENERAL CONSIDERATIONS.--Radio engineering depends primarily upon the manner in which radio frequency energy is propagated through space. It is therefore important that the radio engineer have a fundamental knowledge of the mechanism of radiation, whether he is in the transmitting or receiving field. The desired fundamental characteristics of the antenna systems in either case are about the same, because an efficient transmitting antenna is also an efficient receiving antenna at the same frequency.

The requirements of an antenna system may vary from those of broadcast transmission, where a very strong signal is required along the surface of the earth within a comparatively small area known as the service area, to those of long distance transmission where it is desired to send the greatest amount of signal energy to a point several thousand miles away. In the former case long distance transmission may be very undesirable; in the latter case, local transmission is undesirable.

The broadcast receiver engineer has to design an antenna system that will pick up signals from all directions and over a wide band of frequencies, whereas the communication engineer may have to design a receiving antenna that will pick up energy from a single transmitter, and that will exclude energy from other transmitters operating at other frequencies and located in other directions.

In Fig. 1 is shown the pattern of a transmitting antenna that radiates equally well in all directions, whereas in Fig. 2 is shown the pattern of an antenna whose radiation is suppressed in a southerly direction. The latter antenna system is more complicated, and employs several elements in the form of an array. In the Civil Airways the exact location of each radio range (directional beacon) station is indicated by a "cone marker beacon." The pattern is shown in Fig. 3, and is produced by a 75-mc. transmitter. When an airplane flies through this cone of radiation the pilot hears a distinguishing signal in his headphones, and a light on his instrument panel flashes on and off.

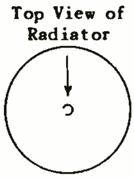


Fig. 1. Pattern of equal field intensity. The circular shape represents equal radiation in all directions.

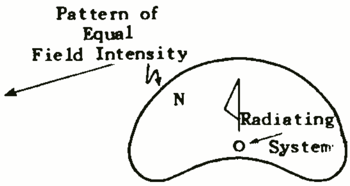


Fig. 2. Radiation to south suppressed.

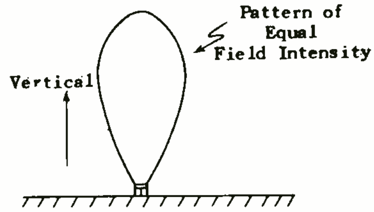


Fig. 3. U.H.F. cone marker system.

In the receiving field a directional antenna may enable the receiver to pick up the desired signal from a transmitter located in one direction, and to reject signals of the *same frequency* from transmitters located in other directions. Directional antennas are also used in direction-finding systems, and in point-to-point communication systems to sharpen the effect of a directional transmitted beam at the receiving point.

FUNDAMENTAL CONCEPTS OF RADIATION.--In order to understand how to design and operate radiating systems it is important to have a physical picture of the mechanism of radiation. It is impossible to make this picture complete without resort to higher mathematics, but a reasonably comprehensive description can be given that will be sufficient for most practical purposes.

Radiation has to do with the way in which electric and magnetic fields are set up by moving charges*. When the charges are moved, the electric

(*) In a previous lesson it was stated that a current flow is due to the motion of electrons (negative charges) through a conductor. This is perfectly true, and represents the current flow in most radio circuits. But in some circuits, such as electrolytes (solutions of chemical salts) the current flow is equally divided between negatively charged atoms (negative ions) flowing through the electrolyte in one direction, and positive ions flowing through the electrolyte in the opposite direction. The two *opposite* flows produce an *additive* effect in setting up magnetic lines of force around the electrolyte, in heating it, and in any of the several ways in which a current flow makes its presence known to the observer. In this lesson, a series of positive charges in motion will be used to represent a current flow and to explain radiation, merely for the convenience in drawing the electric fields emanating from the charges.

lines of force emanating from them tend to move with them. But the moving charges represent a current flow, and establish magnetic lines of force around them. The magnetic lines react upon the electric lines and, as will be shown, prevent the entire electric field from moving instantly with the charges, so that the outermost parts of the electric field are held back. The magnetic lines of force in the outer regions cannot be established until the electric lines in those parts of space move forward to keep up with the charge. There is thus an interaction between the two fields which does not permit *instantly* their establishment farther and farther away from the moving charges, but rather *with the finite speed of light.*

The process by which the electric field lines are dragged forward by the charges, and in so doing establish the magnetic lines of force, is known as radiation.

Since the magnetic and electric fields represent energy stored in space by the moving charges, it is apparent that the process of radiation is the means by which *energy is stored in space.* Thus radiation is not a new phenomenon that appears suddenly at high frequencies in certain special forms of circuits; instead it is a normal phenomenon present at *all frequencies* and in *all forms of circuits.* It is true, however, that *its effects are more pronounced at higher frequencies,* particularly in special shapes of circuits designed to enhance these effects.

ELECTRIC FIELD LINES.--To understand radiation it is necessary to have a knowledge of some of the fundamental laws of electrostatics and magnetism. This is particularly true for u.h.f. design. Such knowledge is also necessary for the study of electron optics: the methods by which streams of electrons in a cathode-ray tube and an electron microscope, for example, are focused into narrow beams.

Consider two charges of opposite polarity, $+q_1$ and $-q_2$, separated a distance r from one another. By Coulomb's law, they attract one another with a force proportional to their product, and inversely as the square of the distance between them. Stated mathematically, the force is

$$F = K\frac{q_1 q_2}{r^2}$$

The constant K is a factor of proportionality and depends upon the units and the medium in which the charges are immersed. For free space (vacuum) K may be taken as unity (one). The important thing to note is that F is a force *acting through space* between the two charges. Also note that if the distance r is *doubled*, the force becomes *one-quarter as great as before;* if the distance is *tripled*, the force becomes *one-ninth*, and so on.

At first it was believed that this force represented "action at a distance," i.e., the ability of one body to push or pull on another without having any physical connection with the other. This idea did not appeal to Faraday, who suggested that certain lines or tubes of electric force connected the two charges, and that these lines tended to contract --like stretched rubber bands--and thus pull the charges together. A strong charge had many tubes or lines associated with it, and if the other charge were also strong (and of opposite polarity) it would take on a large number of lines from the first charge, and so be pulled to it with a strong force.

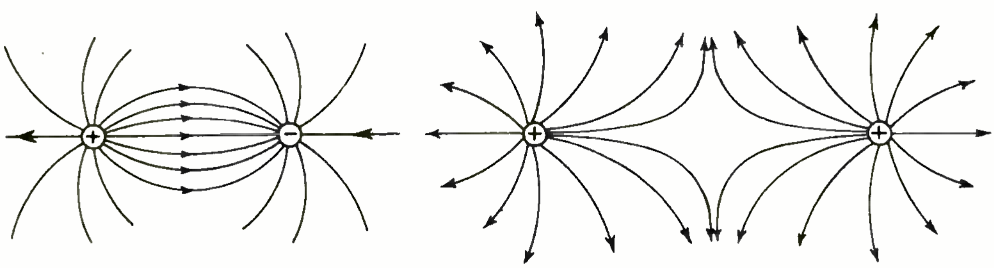


Fig. 4 Fig. 5

A picture of the electric lines joining the two charges is shown in Fig. 4. Note the bowed position of most of them and the fact that they do not cross one another. Faraday explained these shapes on the basis that the lines themselves repelled one another sideways, and thus forced one another out into the shapes shown. However this stretches the lines, and they assume shapes such that the lateral (sideways) repulsion is just balanced by the tension produced in them by their stretching.

The lateral repulsion between lines also explains why *like charges repel one another.* In Fig. 5 two *positive* charges and the associated fields (groups of electric lines) are shown. Note how the lines curl away from one another and press sideways against one another. The lateral repulsion is just as strong as the tension in the lines. This means that the *force of repulsion* between two *like charges* is just as great for a *given distance r* as the *force of attraction* between two *unlike charges* separated by the same distance.

The electric field lines (also called electric lines of force and electric flux) normally start out from a positive charge and end on a negative charge or charges. In many problems in electric theory the behavior of a single charge in space is studied. Suppose this is a positive charge. The question naturally arises as to where its electric field lines go in order to terminate on negative charges. The answer is that since by hypothesis this charge is alone in space, its field lines must proceed out to infinity before they can find negative charges on which to terminate. This is also true of a number of positive charges strung out along a line. No electric line emanating from one can terminate on another since they all have the same polarity (positive). The field pattern must be as in Fig. 6. For simplicity, only eight field lines are shown for each charge. Note that each group of eight lines lies in a plane perpendicular to the line of charges AB, and that these field lines proceed radially outward from the charge, like spokes from the hub of a wheel. No line from one charge invades the territory of the next charge because a corresponding line from this charge would repel it away from that territory. That is why each group of lines lies in a plane perpendicular to AB.

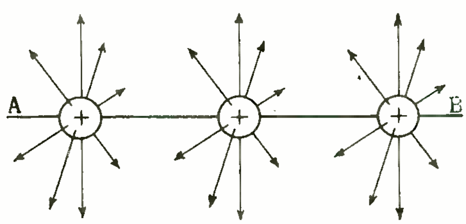


Fig. 6

If there were any negative charges present anywhere near these positive charges, some of the lines would be distorted from their radial positions and would terminate on the negative charges instead of proceeding out to infinity. The field pattern would thus be distorted. *But the important thing to note is that even in this case there would still be some lines proceeding out to infinity;* in short, the field lines *emanating* from a positive charge, or those *terminating* on a negative charge, are of various lengths, and some are even of infinite length. This is important, because it is the longer electric lines of a field pattern that are most instrumental in producing radiation.

Coulomb's law gives the force acting between two charges separated by a certain distance. This force will be different if the two charges are immersed in another medium. For example, if the two charges are placed in kerosene instead of a vacuum, and *separated by the same distance,* the force will be reduced in the ratio of 1 : 2.5, or will be only 40 per cent as great. The number of electric field lines and their pattern remains unchanged, but each line seems to have had its tension and its lateral repulsion reduced to 40 per cent of its original value.

The charges would have to be increased 2.5 times *before the force would reach its original value.* This in turn would mean *2.5 times as many electric field lines* in the pattern. Thus, if a *fixed* voltage is applied between the two plates, then if the space is filled with kerosene instead of a vacuum the number of charges on the plates and the field lines in the space will be 2.5 times as great. This means that the *capacity* of the condenser is 2.5 times as great.

This property of kerosene and other insulators is measured by a quantity called the dielectric constant, denoted by the Greek letter ε (epsilon). It gives the *reduction in the force* between *fixed charges* when immersed in the medium instead of in a vacuum, or alternatively, it gives the *change* in the *number of charges* and *electric field lines* when the *force (hence voltage)* is *maintained constant.* In short, it gives the increase in capacity of a condenser having this dielectric material instead of a vacuum between its plates. The range of ε is from unity (one) for a vacuum and most common gases (including air) to over 100 for certain special ceramic materials recently developed.

The strength of the force between charges in free space is measured by the number of lines connecting them. In general, if attention is focused on a square inch or square centimeter in free space through which field lines are passing, the strength of the field is given by the number of lines that pass through that area, and is denoted by the letter E. This also gives the strength of the force on a particle in free space having *one unit of charge* located at that point in the field. To summarize, the strength of the electric field at any point in space is known as its

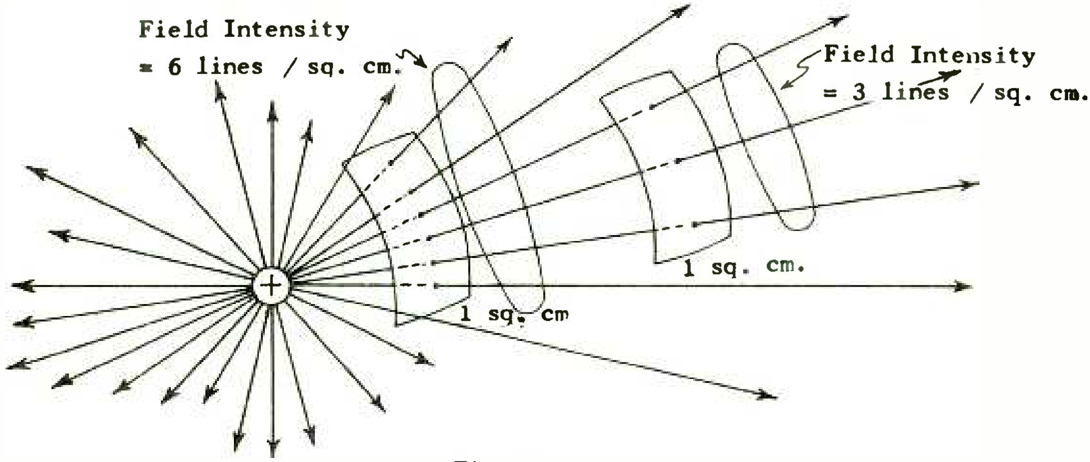


Fig. 7

field intensity, and is measured by the number of lines passing through a unit area, such as one square centimeter, enclosing that point. See Fig. 7.

One thing must be emphasized. Faraday's concept of tubes or lines of force connecting unlike charges is a convenient physical picture. It must not be interpreted too literally: it must not be thought that in between two lines there is no force exerted on a little charged particle placed at such a point. Actually the forces are *uniformly distributed* throughout space as a kind of strain, but in visualizing the action of attraction or repulsion and in evaluating the electric field intensity, it is convenient to think of *individual lines* in space.

MAGNETIC FIELD LINES.--It was stated that radiation is due to the interaction of the electric and magnetic field lines. It is therefore necessary to review the methods by which magnetic lines of force are set up, and in what shapes or patterns they form themselves.

When charges move, their motion constitutes an electric current flow. If there are n charges, each having the same magnitude of charge, q, and they all move with a common velocity, v, then the strength or intensity of current flow is

$$i = nqv$$

It is immaterial whether these charges move in a vacuum, as in a vacuum tube, or in an antenna; the motion represents a current flow of strength as given by the above equation. But as soon as the charges move a new phenomenon appears--lines of force that act not on electrical charges at rest, as do the electric field lines, but rather on compass needles and other magnetic objects. These new field lines are identical to those produced by magnetized compass needles and the like, and are known as *magnetic lines of force or flux*. A group of magnetic lines is known as a *magnetic field*. The field remains fixed in space as the succession of charges whose motion produces it, passes through it.

The magnetic lines exhibit some properties similar, and some properties dissimilar to those of electric field lines:

(1) Unlike the electric field lines that terminate on charges the magnetic lines are endless, and form circles around the moving charges. As shown in Fig. 8, if the charges move from left to right, the magnetic flux is set up in concentric circles about the charges in the direction shown by the arrows. If the north pole of a long magnetized needle is brought near such a circle of flux, it will be pushed away from the circle in the direction indicated by the arrow on the flux line. A convenient way to remember the two directions is to use the right hand as shown in Fig. 8. If the thumb points in the direction of the current flow, then the other four fingers will indicate the direction of the flux lines. It must be noted that in addition to the circles shown there are an infinite

number of other such circles, within and without those shown.

(2) The magnetic field strength or intensity is measured in the same way as that for the electric field lines: *the number of magnetic lines that pass through one square centimeter about a point in space represents the magnetic flux density at that point.* For free space the symbol normally employed for the flux density is H. It is directly pro-

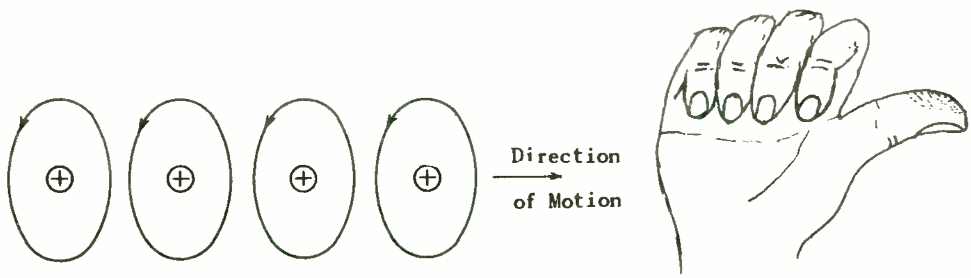


Fig. 8

portional to the current flow.

(3) As in the case of the electric field lines, the magnetic force is *uniformly distributed* in space in the form of a strain, but is more conveniently represented by discrete (separate) lines.

(4) Like electric field lines, magnetic lines tend to contract and also to repel one another laterally. The magnetic flux pattern obtained in any one case results from the balancing of the forces of contraction in any one circle of flux and those of repulsion between that circle and its neighboring circles. Ordinarily the pattern is that indicated in Fig. 8--concentric circles of flux in planes perpendicular to the direction of current flow. Note that they do not cross one another.

(5) A significant point is that *the magnetic flux lines passing through any point in space are perpendicular to the electric field lines passing through that point.*

(6) Corresponding to the dielectric constant for electric fields, there is a constant known as permeability for magnetic fields. It is denoted by the Greek letter μ (mu). It represents the ratio of the number

of lines of flux set up around a current in some particular medium to that set up in a vacuum (free space). For most materials μ is unity, but for iron, nickel, cobalt, and their alloys (the so-called *ferromagnetic* materials), its value may rise to several thousand. The inductance of a coil wound around a core is determined by the permeability of the core. In addition, μ, in conjunction with ε, determines the velocity of propagation of an electromagnetic wave, its reflection, etc.

MAXWELL'S HYPOTHESIS.--Before Maxwell's time it was assumed that all the circles of magnetic flux were set up entirely by the *moving charges* passing through their common center. Maxwell advanced the hypothesis that the electric field lines associated with the moving charges could also set up magnetic lines of flux by virtue of their motion. In other words, if a portion of an electric field line (emanating from a positive charge) were suddenly moved broadside to itself, its motion would constitute a local current flow and would produce a circle of flux *perpendicular to its motion and its direction*, even though the charge from whence it came was stationary.

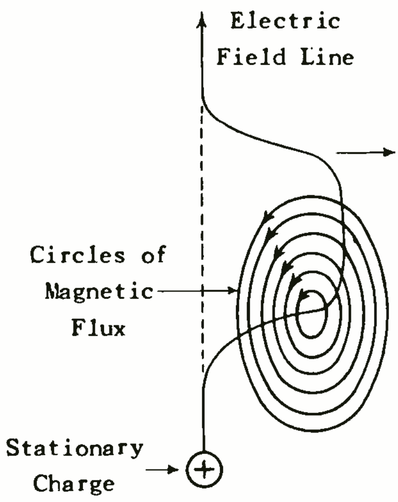


Fig. 9

Such a condition is shown in Fig. 9. A segment of the electric field line is displaced from its normal (dotted line) position to the right. Circles of magnetic field lines are set up as shown. This was a new idea. It indicated that the electric field lines set up between two condenser plates, for example, could be considered a (displacement) current, and would set up magnetic flux. But it led Maxwell to an even more important conclusion: it indicated that electromagnetic waves could be set up in a medium, such as space, and produce the radiation phenomenon that is the basis of radio communication today, and is the subject of this lesson.

FARADAY'S DISCOVERY.--Prior to Maxwell's time, Faraday had made a momentous discovery that was the counterpart of Maxwell's hypothesis. Faraday found that a *moving* or a *changing magnetic field* in space could produce or induce an *electric field* in that space. This discovery forms the basis of present-day generator and transformer action. (Joseph Henry in America made this same discovery independently of Faraday, but unfortunately published his results a little later.)

The electric field lines produced by a varying magnetic field are exactly similar to those set up by electric charges *except* in one particular: they form *closed loops* that encircle the varying magnetic loops, as shown in Fig. 10, whereas the electric lines produced by electric charges *end* or *terminate* on charges of opposite polarity.

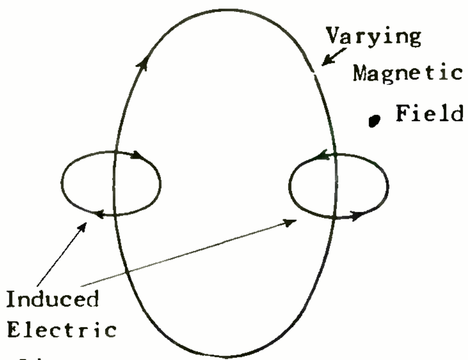


Fig. 10

The closed loops of electric field are *present in space*. If a conductor in the form of a loop is placed so as to coincide with an electric field loop, electrons in the conductor will be forced around it by the electric field loop, and will represent an induced current flow. The *total force* around the conductor loop, due to the electric field loop, is a measure of the *induced voltage*. *The important thing to note, however, is that the electric field loop, and therefore the induced voltage, are present whether or not a conductor is placed in that space to detect their presence.*

RADIATION.--The preceding sections have discussed the nature of electric field lines, magnetic field lines, the production of magnetic fields by moving or varying electric fields (Maxwell's hypothesis), and the production of electric fields by moving or varying magnetic fields (Faraday's discovery). We are now ready to investigate the phenomenon of radiation. For this purpose it is preferable to employ the line of positive charges isolated in space as shown in Fig. 6 (even though this is not an arrangement used in practice), because the electric and magnetic field patterns of such charges will be relatively simple, and the process of radiation will be easy to follow.

Suppose, first, that these charges have been at rest for an infinite time. The electric field lines will have had time to form themselves into the radial pattern shown in the figure, and no magnetic lines will be present because there is no motion. Now suppose that an electric field is produced in some manner *solely along the line of charges*, and that it exerts a force on them that accelerates them from rest to a velocity v to the right during a certain time interval.

If the radial electric field lines associated with the charges were displaced throughout their lengths *instantly* to the right along with the charges, they would set up, by Maxwell's hypothesis, circles of magnetic flux *instantly* throughout all space. Consider first a *very small* circle of magnetic flux set up directly around one of the moving charges. This is shown in Fig. 11. A moment before there was no circle of magnetic flux; now there is one due to the motion of the charge. This represents a *change* in magnetic flux: from zero to some intensity. By

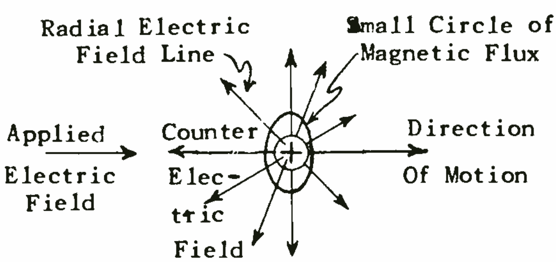


Fig. 11

Faraday's rule, an electric field loop is set up. A short portion of it proceeds from the charge to the left, and represents a counter electric field to the applied electric field. The total counter electric field due to all the charges set in motion corresponds to the *c.e.m.f. of self-inductance*. It is balanced by the applied electric field.

So far nothing unusual has occurred. All that has been described is the mechanism of self-inductance. But now consider segments of the radial electric field at *a greater distance* from the charge. When they begin to move, like portions of the spokes of a wheel moving broadside, they produce a circle of magnetic flux of *greater radius.* This, too, represents a *change*--from no magnetic flux to some magnetic flux in *this region.* By Faraday's rule electric lines are induced also in this region. As stated previously, these electric lines form closed loops, but no restriction was made as to the size of the loops. If there were only one charge under consideration the electric lines would tend to form loops around the magnetic circle similar to those shown in Fig. 10. But since a *whole line of charges* (of indefinite length) is being considered here, the electric loops of one circle of magnetic flux would have to cross the loops of *neighboring* circles of magnetic flux. Since this is not permitted the induced electric field due to the circles of magnetic flux of the *whole line of charges* takes on a *resultant* shape as shown in Fig. 12. Note that they do not even veer around beyond their circles of magnetic flux to close, but instead proceed radially outward to infinity before closing on themselves. This is because *still larger circles* of magnetic flux are trying to send electric field lines in the same direction and prevent these electric lines from curling around and forming shorter closed loops. Yet these do crowd out, to a certain extent, the induced electric field lines of the still larger circles of magnetic flux, thereby decreasing their intensity.

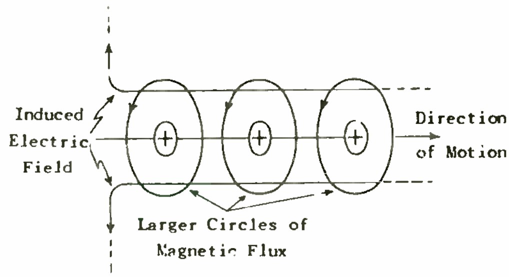


Fig. 12

The situation is therefore as follows. As the charges move, they and their associated radial electric field lines produce circles of magnetic flux around them. The establishment of the magnetic lines produces electric lines *opposite* to the *direction of motion* of the *charges.* The lines produced by the *small circles* of the magnetic flux balance the *applied* electric field. But the lines produced by the larger circles of magnetic flux are outside and around the applied electric field and not in line with it. They are therefore not balanced or counteracted by it, and so can produce effects that the lines due to the small circles are unable to produce.

The effects produced are shown in Fig. 13. For clarity only one of each important component is shown, such as one charge, one circle of magnetic flux, one radial electric field line, etc. AB represents the portion of the radial field line next to the positive charge. It has been displaced together with the charge to which it is attached. BC represents the next portion of the electric field line, which normally would proceed directly in line with AB. But through point C a circle of magnetic flux F is just being established, and its establishment induces an electric field line, CD, which is at *right angles* to BC. Since there can be no crossing of field lines there must actually be a resultant line BD produced, i.e., BD is the resultant of BC and CD. This in turn means that the next vertical portion of the radial field line, DE, passes through point D instead of point C, or is *behind* or *retarded* with respect to the lower portion AB.

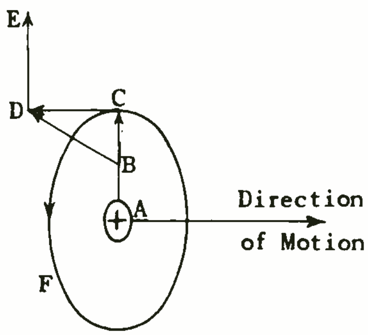


Fig. 13

The effect of the establishment of circles of magnetic flux is to induce right angle components of electric field which delay the portions of the *radial* electric field lines beyond them. Thus DE has not moved as far as the charge and portion AB have moved. *Its lack of motion means that it does not represent as great a (displacement) current flow as segment AB represents*, so that the circle of magnetic flux that ED sets up will be much weaker than F.

However, once circle F has been set up, it no longer represents a *variation in magnetic flux*, but merely a *steady value, whereupon component CD disappears* and kink BD becomes *BC*, and *DE* now *starts to move over in line* with *ABC*. *But this represents a displacement current in* *this region of space*, and so a larger circle of magnetic flux is set up passing through a point above C. This larger circle produces a right angle electric field above CD, kinking DE into a slanting line similar to the way BC was kinked into line BD. In other words, DE does not quite shift over immediately into line with ABC, but more gradually.

The actual shape of a radial field line is not as sharply kinked as Fig. 13 indicates. The effects described above have been magnified to make the picture clearer to the student. Actually they take place over a range of lengths in graduated fashion. A more exact picture is that shown in Fig. 14. Again, for clarity, only one charge is shown. AB represents the position of the radial electric field line when the charge is at rest, position 1. When the charge is accelerated to the right to position 2, it moves and sets up magnetic flux lines which kink AB into the shape CD. The lower portion of CD is nearly in line with the charge, but the upper portions slope off to the left, until from D upward the line has hardly moved. This shape indicates that practically all the magnetic circles of flux have been established around the charge, but less and less larger circles of flux have as yet been established.

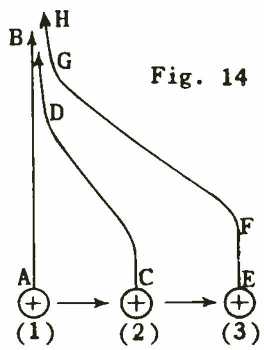


Fig. 14

As the charge continues to move to the right and reaches position 3, the radial electrial field line is distorted to the shape EFGH. The portion EF is practically in line with the charge; the portion FG is greatly kinked; and the portion GH has hardly advanced from its original position. In the region EF most of the circles of magnetic flux have been set up, and the *storing of magnetic energy* in this region is practically complete. In the region where FG is present magnetic lines are being set up (magnetic energy is being stored) and, as explained previously, are inducing electric field components which are responsible for the slope of FG, and also responsible for the fact that the magnetic lines themselves are not as abundant as they would be if FG could snap over to the right. In the region GH there are very few circles of flux because the radial line has hardly moved to the right.

As fast as the magnetic lines are produced the kinked portions of the radial electric lines snap over, but this only produces kinks *a little farther out* on the radial lines. It is thus apparent that the kinks in the lines *travel* outward; *the velocity with which they travel is that of light, namely 3 x 10^8 meters/sec.*

But such a motion radially outward *represents a current flow in this direction.* This current flow is relatively large, for the velocity of the kinks is that of light. This *radial* current produces *additional* magnetic lines. These lines would link the kinked portions individually except for the fact that the kinks of *all* the radial electric field lines from a charge form a *circular* group extending completely around the charge from which they originated. Consequently, the additional magnetic lines produced by the *group* of kinks form circles around *all* the kinks instead of around each *individual* one, *in order not to cross one another.* Thus these additional magnetic lines produced by the radial motion of the kinks form circles around the charges of the *same form* as the original circles of magnetic force that were produced by the lateral (left-to-right) motion of the electric field lines.

This can be summarized as follows:

(1) The charges are accelerated from left to right in the above example.

(2) They produce concentric circles of magnetic flux around them.

(3) These circles induce electric field lines from *right to left.*

(4) These lines, in vector combination with the *radial* electric lines emanating from the charges, produce a resultant kink in the radial lines.

(5) These kinks delay the left-to-right motion of the radial lines farther out.

(6) This delays the production of circles of magnetic flux in these outer regions.

(7) The kinks all around each charge travel radially outward with the speed of light.

(8) Their motion constitutes a radial current flow: one at right angles to the current flow represented by the motion of the charges from left to right.

(9) The radial current flow sets up additional circles of flux around the charges in the vicinity of the kinks in the electric field.

(10) This additional magnetic field *accompanies* the kinks and helps to maintain them.

(11) The circles of magnetic flux that are left behind are those due to the left-to-right motion of the *radial* parts of the electric field lines below the kinks, and in line with the charges from which they emanate.

(12) The latter circles of magnetic flux are in proportion to the velocity of the moving radial parts of the electric field lines, and this velocity is merely that of the charges themselves. It is very much less than that of light.

Thus one may speak of four components: two electric, and two magnetic.

(1) The radial components of the electric field lines.

(2) The circles of magnetic flux that the above set up by virtue of their motion in the direction of the charges. These circles appear first near the conductor, and then farther and farther out.

(3) The kinked portions or components of the electric field lines.

(4) The circles of magnetic flux--similar to those of (2)--that are produced by the radial motion of the kinks. These additional circles of magnetic flux travel with the kinks, i.e., expand outward. At any point where such circles appear, there remain some circles of magnetic flux described in (2), while the rest of the circles continue to expand outward.

Hence an observer stationed at some point in space would see first a stationary radial electric field line passing through that point. No magnetic flux would be present. Then a kink in the radial electric field line would pass by with the speed of light. As it passed by, magnetic circles of flux would appear, passing through the point of observation, and encircling the distant charge whose motion caused the above phenomena. Some of these circles would expand outwardly in company with the kinks and pass by the observer, others would remain in his locality. In addition, radial electric lines would be seen, but now they would be in motion. Their *direction of motion* would be at right angles to their *direction of pointing*, which is radial, and their velocity would be that of the charge from which they originated.

Suppose now the charges are suddenly brought to rest. The *current flow* becomes zero, and the magnetic lines must cease. This means that at any point where a flux line existed there is now no such line, and this represents *a change in the opposite direction* from that of establishment of the magnetic field. By Faraday's rule, an electric field will be induced in the *opposite direction*. The process is exactly similar to that previously discussed: a kink, in the *opposite direction*, travels outwardly along each radial electric line with the speed of light, and thus brings successive portions of the line to rest and simultaneously wipes out the magnetic circles farther and farther away from the charge. The electric line now has the appearance of that shown in Fig. 15. AB represents the reverse kink that is bringing the electric field line to rest along the associated charge. BC represents a portion of the field line that is still travelling with the velocity the charge had before it was brought to rest. CD represents a portion farther out *that is just being brought up to that velocity*, and finally DE is the remaining portion.(extending to infinity) *that has not even been accelerated to the*

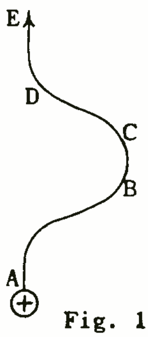


Fig. 15

right. In the region of AB magnetic circles of flux are being wiped out, and the energy they have stored in that space is being returned to the circuit in the form of an *inductive rise in voltage*, i.e., a voltage trying to keep the charges moving and thus able to *produce* work in the system. In the region of BC energy is still stored from the previous acceleration of the charge. In the region of CD energy *is just being stored* from the previous acceleration, and in the region DE energy has not as yet been stored, but *will be* when kink CD gets out there. But the reverse kink AB travelling outward is also accompanied by magnetic circles of flux, whose directions are opposite to that of the previous circles. These circles cancel the previous circles, i.e., magnetic flux is being wiped out. But their number also exceeds the normal magnetic flux in the region, so that at any point in the region there is momentarily a *net* magnetic flux in the reverse direction. However, as these reversed circles expand outward in company with the reverse kinks, zero flux is left behind together with *stationary* radial electric field lines.

If the stationary charges are now accelerated to the left, the reverse kinks will be lengthened, and the same state of affairs as first pictured will occur, the only difference being that circles of magnetic flux in the reverse direction will be set up, and through them will move radial electric lines to the left, with the velocity of the charges now moving to the left.

Finally, if the charges oscillate back and forth (alternating current flow), a succession of kinks will be developed along the radial electric lines, and these kinks will be alternately in one direction and then the other. Circles of magnetic flux will be set up; some will circle around in one direction, others in the opposite direction. A certain proportion of these circles can be regarded as fixed in space, and are produced by the moving radial components of the electric field lines. (How an electric field line can be resolved into radial and kinked components will be described shortly.)

These kinks in the electric field lines and the additional magnetic fields produced by their motion may be a surprise to the student. Apparently the earlier simpler explanation given that the motion of charges, such as electrons, and representing a current flow, produces a magnetic field, is so approximate as to be erroneous. Apparently the situation is much more complex than that previously presented. This is true, but the original, simpler explanation is entirely satisfactory at *low frequencies*. The kinks in the electric field lines are negligibly small, as is therefore the momentary excess magnetic flux at any point. But at high (r.f.) frequencies the new phenomena will be, as a general rule, appreciable in magnitude, and it was not until means had been devised to generate high frequency currents that these effects could be detected. Maxwell's electromagnetic theory was published about 1868, but it was not until 20 years later that Heinrich Hertz experimentally proved the existence of radio waves.

The four components of the two fields previously enumerated are conveniently classified into *induction* and *radiation* fields.

The induction fields refer to the *radial* components of the electric field lines, and to the circles of magnetic flux produced by the lateral motion of the above radial components.

The radiation fields refer to the kinks in the electric field lines, and to the additional circles of magnetic flux produced by their motion radially outward. The induction and radiation fields can be distinguished as follows:

In Fig. 16(A) is shown a radial field line kinked by the acceleration of the charge. Associated with the field line are shown two magnetic flux lines--h_1, that is being established, and H_2, already established. The electric line can be broken up into horizontal and vertical components as shown in (B). Thus the straight portions, E_4, E_3, and E_2 represent the induction components of the electric field line, and E_1 represents the radiation component of the electric field line. Note how the actual kink E_5 can be resolved into E_2 and E_1. If E_5 is appreciably curved, then it can be broken up into a number of small segments as shown in (C), each of which is practically straight, and the resolution into vertical and horizontal components performed on each segment. The radiation field will be the sum of all the horizontal components, or AB + BC + DE + EF + GH, whereas the induction field will be LK + KA + CD + FG + HI + IJ.

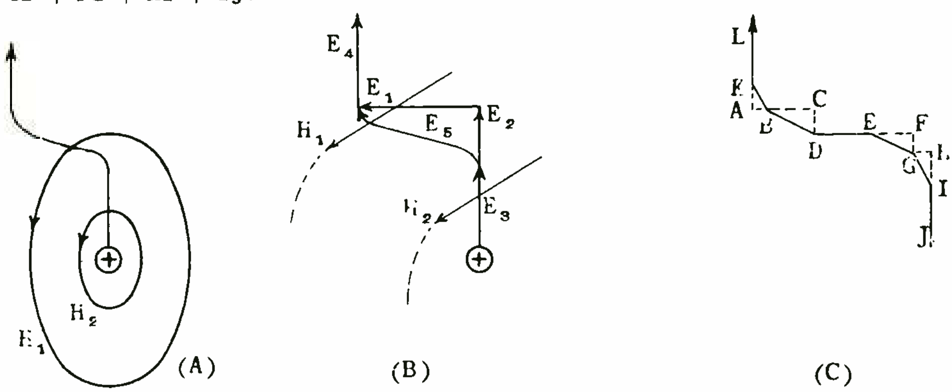


Fig. 16

The induction and radiation magnetic fields are distinguished by the fact that the induction field remains fixed in space, whereas the radiation field moves outwardly along with the radiation electric field. The two fields also differ in time phase, but this will be discussed later.

The induction field represents the storage of energy in space. In the particular example chosen, the storage is predominantly magnetic in nature: magnetic flux is being set up in space, and associated with this flux is a certain amount of energy.

The radiation *magnetic field, in conjunction with the radiation electric field,* represents energy, also. The combination is called *electromagnetic* or *radiant* energy. It is characterized by the fact that it *moves* through space, and a certain amount passes through, say, a square foot of space every second. Since energy per unit time is *power,* one can say that the charges radiate power into space. This power can be shown to be equal to the product of the magnitudes of the two fields. The magnetic radiation field has the direction of H_1 in Fig. 16(B), and is that part of H_1 which moves with E_1 (whereas the portion of H_1 that remains at that point is the induction component of the magnetic field). In Fig. 16(B) the radiant power is proceeding upward at the point in space under consideration, i.e., perpendicular to E_1 and H_1. This is a characteristic of radiant power: it has direction, and can therefore be represented by a vector. The vector is known as the Poynting vector after a mathematiciam named Poynting, who first developed this concept. It is particularly useful in calculating the radiation resistance of an antenna, although it applies to electrical power flow in *any* circuit.

VARIATION OF INDUCTION AND RADIATION FIELDS WITH DISTANCE.--Both the induction and the radiation fields decrease in strength or intensity as one proceeds farther and farther from the source.

(1) The strength or intensity of either the radiation electric field component or the radiation magnetic field component varies *inversely as the distance* from their source. Since the radiation power is equal to their product, it must vary *inversely as the square of the distance*. For example, suppose that at some distance r, the electric radiation field is E, and the magnetic radiation field is H. The radiant power P is then E x H. At twice the distance, or 2r, the two radiation fields are half of their previous values, or E/2 and H/2, respectively. The radiant power at this point is

$$P' = \frac{E}{2} \times \frac{H}{2} = \frac{E \times H}{4} = \frac{P}{4}$$

or it is one quarter of what it was at the distance r.

This rate of decrease is merely a matter of energy spreading out uniformly into space. It is interesting to note that this *dilution* or *attenuation* of the radiation fields is actually less for *long distances of transmission* than the exponential type of dissipation encountered in a long transmission line, occasioned by the losses in a line, because an exponential (percentage) type of loss can total to a very large amount over any great distance. Hence radio transmission *in this respect* is actually superior to line transmission without benefit of repeater amplifiers, over long distances.

(2) The intensity of either component of the induction field varies essentially *inversely as the square of the distance*. Near the source either is stronger than the corresponding radiation component; at a distance of $\lambda/2\pi$, or roughly 1/6 of a wave length (to be discussed), the two types of fields are equal in intensity; beyond this distance the radiation field predominates. Since the usual distances of transmission are many wave lengths, reception is ordinarily that of the radiation fields.

The above statements must not be misinterpreted. For example, in the case of a directional radiating system such as an antenna array, one cannot measure the intensity (or field strength, as it is often called) in *one direction*, and then expect that the field strength in *another direction twice as far away* will be one half as great for the electric component of the radiation field, as an example. It may be that the field strength in the latter direction is twice as great rather than one-half as great, because the system has purposely been designed to radiate *more strongly* in this direction than the other. It is evident, then, that the variation in field strength with distance is with reference to a *fixed direction* for the measurements.

VARIATION OF THE RADIATION FIELD WITH FREQUENCY.--The energy radiated per unit time, or power, varies as the *square* of the frequency at which the charges oscillate. This statement requires qualifications that will be given later, but is essentially true, and explains why it is necessary to go to the higher frequencies in order to obtain appreciable radiation from antenna structures of reasonable size and efficiency.

The example of the moving charges can be used to show why the above law of variation is so. The radiation component is the *horizontal* component of a kink in a field line. The greater the number of such horizontal components that pass through an area of one square centimeter at any given point in space, the greater is the intensity of the electric *radiation* field at that point. It will be shown that the intensity as just defined depends directly upon the *length* of any one kink, and that the length depends directly upon the *frequency* with which the charges oscillate, provided that their motion at all frequencies represents the *same* amount of current flow.

In Fig. 17(A) are shown four charges covering a total length of *a* units, from each of which emanates an electric field having a kink *a* units long. The kinks are idealized into perfectly horizontal directions rather than sloping directions to simplify the discussion. Actually, if the horizontal component of a sloping kink is considered, as was discussed previously, the same result will be obtained as is shown in this figure.

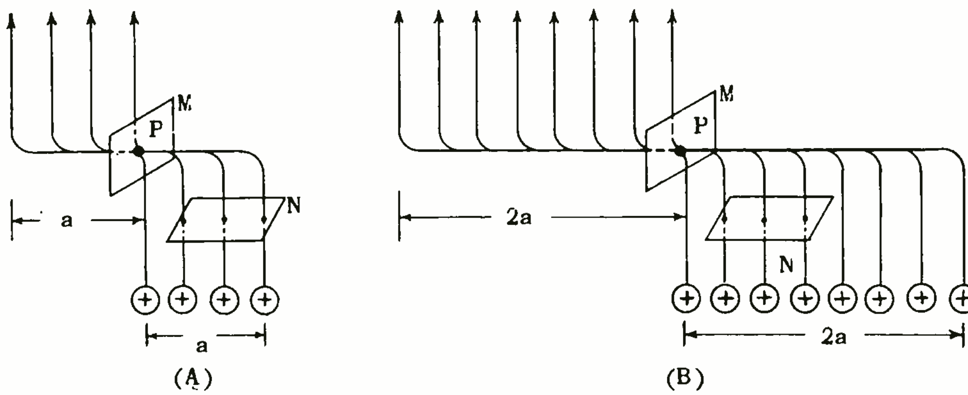


Fig. 17

Suppose it is desired to find the intensity of the radiation electric field at a point P directly over the left-hand charge. To do this a square centimeter of area, M, is drawn around P, perpendicular to the kinks and hence vertical. The number of *horizontal* electric field lines that pass through this area represents the intensity or field strength. In the diagram this is shown as four lines (per sq. cm.). For comparison, another area N, of one sq. cm. is drawn in a horizontal plane. The number of lines shown passing through it is three. Since these are *vertical, displaced* lines, they represent the induction field, and their intensity is 3 lines/sq. cm. (The actual numbers are not important, however, in this discussion.)

In Fig. 17(B) is shown the condition that results when the charges are accelerated twice as rapidly. Each electric field line has a length twice as great, or 2*a*. Through the same vertical plane, M, there pass the horizontal kinks of electric field lines of *eight* charges covering a corresponding distance of 2*a* units. The radiation field strength is now 8 lines/sq. cm. instead of 4 lines/sq. cm., or doubled. At the same time, note that the induction field intensity is still 3 lines/sq. cm. passing through the horizontal plane N.

It now remains to show that Fig. 17(B) corresponds to a current flow of the same magnitude as that corresponding to 17(A), but of double the frequency. As explained previously, the current flow is due to the velocity of the charges, their number, and the magnitude of each charge. For continuous radiation it was shown that the charges must oscillate back and forth, sending out kinks first in one direction and then in the reverse direction. Suppose, therefore, that the charges oscillate in a *sinusoidal* manner, that is, if their *instantaneous* displacements are plotted against time, a sine wave is obtained. The (alternating) current flow depends upon their velocity, and this refers *to the amount of displacement or distance covered in a given time*, such as so many centimeters per second. (It is not necessary that this displacement be only in one direction: the displacement can be the sum of the displacements first in one direction and then in the reverse direction in the given time.)

If the charges oscillate through the same distance or amplitude twice as many times per second (double the frequency) it is evident that the velocity will be twice as great since twice as much distance is covered in the same time, so that the current flow is doubled. Hence, to maintain the *same current flow at twice the frequency*, it is necessary that the charges oscillate through *half the distance*.

Under these conditions it can be shown by the methods of differential calculus that the acceleration, *or rate of change of velocity*, is twice what it was before at the original frequency and same magnitude of current. Since the *length* of the kinks depends upon the *acceleration*, the length will now be doubled and, as was proved previously, this means that radiation field will be doubled. To generalize: if the same current at double the frequency is passed through a radiating system the electric radiation field intensity will be doubled at any point in space.

The radiation component of the magnetic field was shown to be due to the outward motion of the radiation electric field. If the latter is doubled by doubling the frequency, then the radiation magnetic field will be doubled, too, and the radiant power or Poynting vector, which equals the product of the two field intensities, will be quadrupled. (Remember that this is based on the assumption that the current flow is maintained the same at double the frequency.)

At this point it is desirable to discuss one feature of the radiation and induction fields that may appear puzzling. If a flow of current is established in a circuit located, for example, in a laboratory, then experience tells us that practically no magnetic nor electric effects can be detected at a distance, say, of one hundred feet from the circuit. The electric field lines passing through points at that distance are normally considered negligible. Yet the radiation electric field, which is composed of the kinks in these field lines, is appreciable even at distances of many miles. The question arises: how can a *component* of a field line that is negligible in strength, be in itself appreciable? The answer has already been indicated in the preceding discussion. There are always some electric field lines extending from a given charge to opposite charges far away, even though there may be many opposite charges close to the one under consideration. The few long electric field lines can have sizeable kinks developed in them if the frequency is high. Consequently, as shown in Fig. 17(B), the radial electric field intensity at some distance from the charge may be small (3 lines per sq. cm. passing through N), whereas the radiation electric field intensity, the kinks, may be relatively large (8 lines per square cm. passing through M). Thus, the stretching of an electric line into a kink enables it to pass through more areas, as it were, and so momentarily represent a greater field intensity than it otherwise would at any point. This effect is greater at higher frequencies because the kinks are longer.

In a similar manner, the magnetic effects at low frequencies (which are practically those of an induction nature) are practically negligible at appreciable distances from the source. The magnetic field is due practically entirely to the relatively slow motion of the radial components of the electric field; the motion is at the same velocity as that of the charges from which the electric field originates.

But at high frequencies, the magnetic effects at appreciable distances from the source are due only in part to the relatively slow motion of the radial components of the electric field. In addition to these are the magnetic effects of the kinks in the electric field, and since the kinks represent a relatively strong electric field (as described above), and since these kinks are travelling with the speed of light, the additional magnetic effects (radiation magnetic field) are relatively strong. Thus, a circuit whose induction fields cannot be detected a mile away may have a radiation field strong enough to be detected hundreds of miles away.

This viewpoint can also help to explain why the induction field falls off more rapidly with distance than the radiation field. It is sufficient to consider the induction and radiation electric fields, since the corresponding magnetic fields are produced by them and are in proportion to them. As a general rule, the number of electric field lines emanating from a circuit, thins out rapidly with distance, and at twice the distance the field strength, or lines per square cm., is one-quarter as great; etc. The field strength is said to vary inversely as the square of the distance. Reference is of course made to the *induction* electric field.

The radiation electric field, or kinks, become longer and longer as the charge continues to move. Refer, for example, to Fig. 14, positions (1), (2), and (3). Even if the charge is finally brought to rest, the kink continues to grow in length as it proceeds outward. This is because, when the charge is brought to rest, the electric field line emanating from it continues in motion and thus develops a second kink below the first one, and in the opposite direction. This second kink travels outward behind the first one, and brings successive portions of the electric line to rest. But since it takes time to travel, it finds that the successive portions of the line it is going to bring tc rest have moved farther and farther along, thus stretching the first kink. One can say that at twice the distance, a given kink is twice as long.

Now the radiation field strength at any point depends upon the *number* of kinks at that point, and their *length* (as shown previously). The number of kinks is of course equal to the number of lines to be kinked. At twice the distance, the number of lines is *one-quarter as great*, but this is partially counteracted by the fact that the kinks in them are *twice as long*, so that the relative strength of the radiation field at twice the distance is 2 x 1/4 = 1/2 that at the original distance. Thus the radiation field varies inversely as the distance, and the induction field (represented by the unkinked portions or radial components of the electric lines) varies inversely as the square of the distance.

PHASE RELATIONSHIPS.--The magnetic induction field is in time phase with the current that produced it. The electric induction field is in time phase with the voltage. For an inductive circuit such as that discussed (one that is storing magnetic energy) the current lags the voltage by 90°. *Hence the induction magnetic field lags the induction electric field by 90°.*

The radiation electric field is proportional to the acceleration, as is also the radiation magnetic field, since this is produced by the constant velocity of the radiation electric field, and is therefore directly proportional to the latter's intensity. By the methods of differential calculus it can be shown that if the charges undergo a sinusoidal *displacement*, owing to and in phase with a sinusoidal impressed voltage, then the *velocity* of the charges will be sinusoidal in nature (when plotted against time) and *90° leading the* displacement. In addition it can be shown that the *acceleration* will be sinusoidal in nature, too, and *leading* the velocity by *another 90°*, or the displacement by a full *180°*. This means that the radiation electric field will be 180° out of phase with the applied voltage, as will also be the radiation magnetic field, in view of the remarks made at the beginning of this paragraph. The time vector relationships are therefore as shown in Fig. 18, and should be studied in conjunction with a rereading of the above two paragraphs.

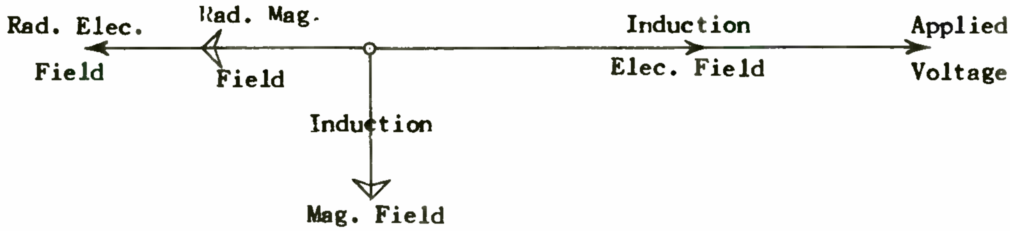


Fig. 18

The student should also note that both in the case of the induction and the radiation fields *the magnetic lines are always perpendicular to the electric lines*, i.e., the two are in space quadrature.

The example chosen above was admittedly not a practical one, but it lent itself very well to the exposition of the mechanism of radiation. Since it concerned a circuit that stored primarily magnetic energy, it represented in a sense the radiation from a loop antenna. Radiation is more often accomplished from a portion of a circuit storing primarily electrostatic energy, that is, a condenser. The action of this, or any actual, practical circuit, is more involved that the simple configuration cited previously, but still depends upon the process of radiation described above.

RECEIVING ANTENNA.--If anywhere in space a conductor is placed parallel to the kinks passing through that region, a voltage will be induced in the conductor of a magnitude proportional to the strength of the radiation electric field (number of kinks per sq. cm.). When the kinks face in one direction, the voltage set up in the conductor will be in that direction; when the kinks face in the opposite direction, the voltage set up will be in the opposite direction. Thus an alternating voltage is induced in the conductor of a frequency equal to that of the source of the radiant energy, and the conductor is known as a receiving antenna. If it be connected to the input circuit of the receiver in a manner similar to that shown in Fig. 24, where terminals AA' would connect to the input of the receiver instead of to the source of r.f. power, then currents of the same frequency will flow and set up the desired voltage across the first tube of the receiver. The successive tube stages would then amplify this voltage, then rectify it, converting it to audio frequencies (if the original r.f. wave were modulated), and then amplify it again until it were powerful enough to actuate a loudspeaker.

One can explain the production of the voltage in the receiving antenna alternatively on the basis of the wire being cut by the expanding circles of the radiation component of the magnetic field. This gives exactly the same value of induced voltage as the radiation electric field, as indeed it should, since the two components are just strong enough to produce one another farther and farther out in space, and thus sustain one another. It must be stressed, however, that the total voltage induced in the receiving antenna can be calculated on the basis of *either* field alone, *and is not the sum of the effects of both fields.* This is because they are not two independent causes; rather, either can be looked upon as the cause, and the other as the effect, so that either may be regarded as setting up the voltage in the antenna.

In general, a good transmitting antenna is a good receiving antenna, and in either use an antenna has the same characteristics as to directivity, etc.

ELECTROSTATIC SYSTEM.--Suppose a constantly increasing voltage is applied to the plates of a condenser, so that it charges up at a constant rate. This means that a constant charging current flows into it.

In this circuit electrons are being transported from one plate around to the other, leaving a net positive charge on the former, and forming a net negative charge on the latter. The accompanying electric field lines are whipped around into a new configuration in which they are mainly concentrated between the condenser plates. This whipping around or reorientation of the lines is accompanied by kinks in them which represent the radiation of energy into space to form the *stored electrostatic* energy of the condenser. Since, by hypotheses, the establishment of magnetic lines of force in the other parts of the circuit has presumably been practically completed, but since the voltage across the condenser is increasing proportionately with time, the electric field and its energy to be stored is increasing, and hence is subject to the process of radiation as mentioned above. In other words, the voltage across the condenser has been so chosen as to make this primarily an example of storage of electrostatic energy, in contrast to the previous example, which was primarily one of storage of magnetic energy.

Instead of trying to study the kinks formed in the electrostatic lines in order to analyze the radiation process taking place here, it is simpler and preferable to study the result, from instant to instant, of the whipping around of the lines. As the charges crowd into the plates, more and more electric field lines span the plates. But the field lines repel one another, and can thus be regarded as being forced to expand outwardly from between the plates. This is shown in Fig. 19. The voltage source is not shown, but the electric field lines are portrayed as being forced radially outward. The two horizontal arrows indicate two such radial directions. This

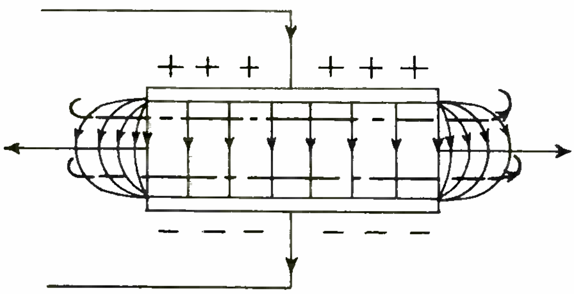


Fig. 19

represents a radial displacement current, and according to Maxwell's hypothesis, is accompanied by closed lines of magnetic flux. These form circles which are perpendicular not only to the direction of motion, but to the electric field lines as well. They are shown by the broken lines in Fig. 19. The combination of the two fields represents a radiation field that is establishing lines of electrostatic flux farther and farther away from the condenser plates and thus storing electrostatic energy in regions more and more remote from the charges.

If now an alternating voltage is impressed instead of the previously assumed constantly rising voltage, the charges will surge back and forth between the plates, and the electric field lines will be called upon to expand and shrink in obedience to the motion of the charges. But owing to the inertia effects in the lines they will be unable to follow this motion in exact time, and the net result will be as before: a certain amount of energy sent out to be stored but never retrieved, i.e., a radiation loss to the circuit. Again it is evident that this loss is greater at higher frequencies, and for appreciable radiation one must go to such higher frequencies.

Another thing (which was briefly mentioned before) is that the shape of the radiating member has a great deal to do with its ability to radiate. In the case of the condenser of Fig. 19 it is evident that most of the field lines are confined to the region between the plates, and few form appreciable fringes around the plates. Such an arrangement is known as a "closed" field; most of the energy is stored directly between the plates, and little in the regions beyond. Such local storage can be accomplished almost instantly, and the energy retrieved equally fast, so that little is lost to the circuit in the way of radiation, except if the frequency is exceedingly high. However, if the condenser plates are in the form of two rods oppositely directed with the generator between them, as shown in Fig. 20, then a large proportion of the electrostatic field is in long fringing loops around the two rods, as shown, and a considerable portion of the total energy is being stored in outlying regions.

The process of attempting to store energy, or radiation, is now considerable even at moderate frequencies, for this is an "open" field.

There is one point about this system, as well as that of Fig. 19, that may be well to discuss at this time. The electric field lines are shown as vertical circles around the two vertical wires (condenser plates) in Fig. 20. In the equatorial plane (horizontal plane passing

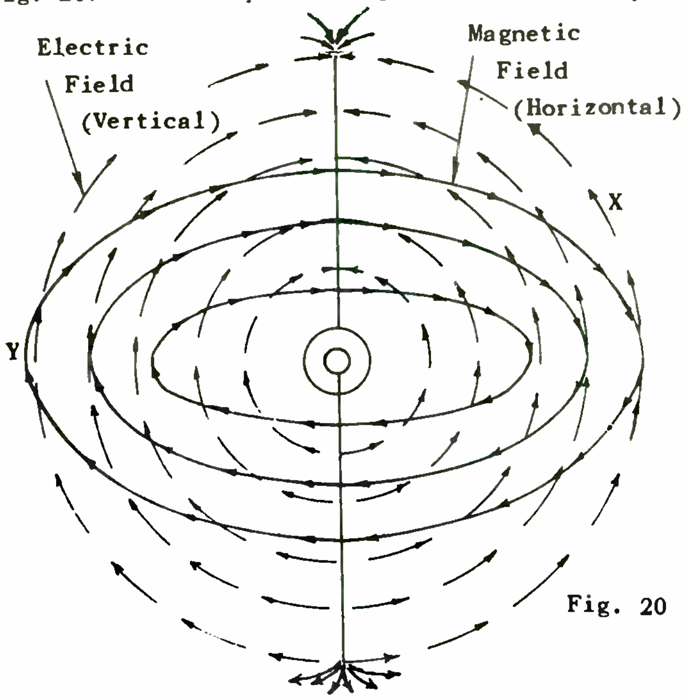


Fig. 20

through the generator), the electric field lines are moving radially outward in a horizontal direction, hence this is the direction of the radiation field. But at point X the expansion is along a radius making an angle of 30° to the horizontal, so that the radiation here is directed at that angle out into space. This means that the direction of radiation has a vertical as well as horizontal component. Indeed, from the figure it appears that radiation is equally strong in all directions, even the radiation in the direction of the wires. Actually the electric field lines tend to crowd around the tips of the two wires on which they terminate, (as shown), and bulge out more in the equatorial plane, so that their rate of expansion and contraction in the latter plane is much greater than at the tips (vertical direction). This means that the most intense radiation is in the horizontal plane and that there is very little radiation in a vertical direction. Such is found to be the case for this arrangement, known as a dipole, and illustrates a very important property of antennas mentioned previously: directivity. The directional properties of antennas are very important and are often enhanced by using two or more elements in an arrangement known as an array. Of this more will be said in succeeding lessons.

A circuit which stores predominantly magnetic energy can also be employed as a radiating system. Indeed, as mentioned previously, the first example of the moving charges illustrated this type of system. However, an actual circuit that radiates (in contrast to the hypothetical arrangement just mentioned) is characterized by an outgoing and return conductor, in which the currents are flowing in opposite directions. Unless this circuit is "opened" up the two conductors will tend to cancel each others' radiation. This can be explained most simply on the basis that if the two sides of the circuit are closely spaced, they can produce very little magnetic flux in the space around them, exhibit incidentally very little inductance, and have little tendency to produce the kinks in their electric field lines that represent radiation. But if the two sides of the circuit are separated a good fraction of the wave length of the radiated energy, radiation will be stronger, and again it is to be noted that the field--this time magnetic--is more open. The circuit now has the appearance of a loop, and is generally known as a loop antenna. It, too, will be discussed in succeeding lessons.

WAVE LENGTH.--Mention has been made of wave length in discussing the radiation from a circuit. In order to explain this concept it is advisable to go back to the first example and consider once again the radial electric lines emanating from the line of positive charges. If the latter are made to move back and forth with a sinusoidal motion, they will produce in their electric field lines a sinusoidal waviness, as shown in Fig. 21. In other words, there are no sharply defined kinks and vertical portions. But at any instant, at certain points of the line the latter will be essentially vertical over a short segment as at A, B, and C; at other points halfway between, short segments will

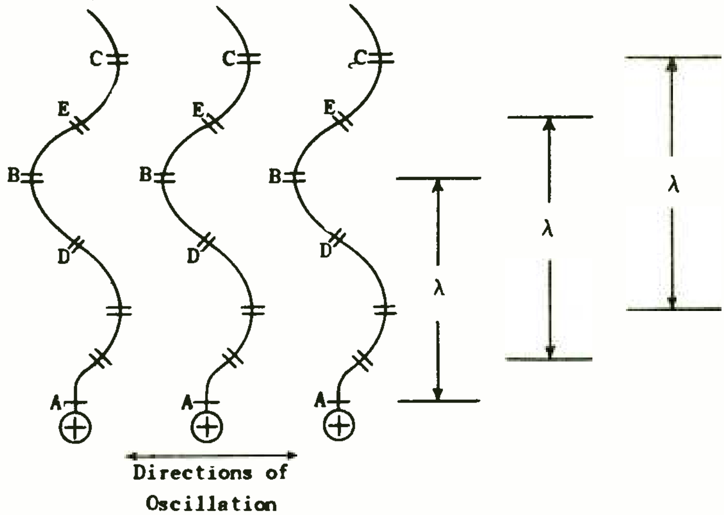


Fig. 21

be more nearly horizontal as at D and E. At the latter points the radiation field *at that instant* is a maximum; at the former points it is zero. But these undulations (waves) in the field lines are travelling with the speed of light, so that a quarter of a cycle later the two sets of points along the field lines will have interchanged their radiation field intensities. Thus, if one were to measure the radiation field intensity at any one point over a *period of time*, he would find that it waxes and wanes and reverses through the same sort of variation at a frequency equal to that of the source. On the other hand, if he were to measure, *at any one instant of time*, the distance between *two maxima in the same direction* or *two corresponding minima*, he would find the distance between *two such corresponding values of field intensity* the same everywhere along the line. This constant distance is called the *wave length*, and is a concept employed for any kind of wave motion--acoustic, vibrating strings, etc. In Fig. 21 is shown such distances. They are denoted by the Greek symbol λ (lambda), which is used for wave length.

The *wave length* of the signal energy in space is determined by the *frequency* of the device that is supplying power to the **radiator.** This device may be an alternator or a vacuum-tube transmitter. The latter is, of course, the one most frequently used in modern radio communication. The older devices include arc and spark transmitters, of which a few may still be in use. To derive the ralationship between wave length, frequency, and velocity of wave propagation, consider a circuit that starts to send out radiant energy with the velocity of light-- 3×10^8 meters/sec. By the end of one second the first undulation in the electric field lines has travelled 3×10^8 meters. Behind it, in equal intervals, are spaced the successive undulations. If the charges in the circuit make f oscillations per second, because that is the frequency of the source voltage, then in one second there will be f undulations along the electric field lines. The length of any one undulation (wave length) is therefore

$$\lambda = \frac{3 \times 10^8}{f} \text{ meters} \qquad (\lambda = \text{wave length, } f = \text{cycles/sec.})$$

At a frequency of 300 kilocycles per second,

$$\lambda = \frac{3 \times 10^8}{300 \text{ kc.}} = \frac{3 \times 10^8}{300{,}000 \text{ cycles}} = \frac{3 \times 10^8}{3 \times 10^5} = 1{,}000 \text{ meters}$$

At higher frequencies there are more undulations in the distance of 3×10^8 meters, or the wave length is shorter. Thus,

at 3,000 kc. = 3 megacvcles or 3 mc., $\lambda = \frac{3 \times 10^8}{3 \times 10^6} = 100$ meters

at 30,000 kc. = 30 mc., $\lambda = \frac{3 \times 10^8}{3 \times 10^7} = 10$ meters

at 300,000 kc. = 300 mc., $\lambda = \frac{3 \times 10^8}{3 \times 10^8} = 1$ meter

Notice how high the frequency must be before the wave length is reduced to 1 meter. This is because the velocity of propagation is so exceedingly high. For comparison, the velocity of a sound wave in air is about 1,140 feet/sec., so that for a wave length of 1 yard (roughly 1 meter) the frequency need only be 1140/3 = 380 c.p.s. For an electromagnetic wave in free space, it is 300 million c.p.s.!

The student may now begin to appreciate why distances for the induction and radiation fields, as well as dimensions of the circuit itself are conveniently given in wave lengths. The distance between two kinks in the electric field that are in the same direction is a wave length. This may represent the separation between two outgoing chunks of energy to be partly lost by radiation and partly stored in space. A point in space several wave lengths from the circuit will evidently be unable to return all the energy stored in it. The actual distance is not important. *It is the distance relative to the frequency, i.e., the wave length, that is important.* The same holds true for the size of the circuit, and how "open" its field is.

The attenuation of the induction and radiation fields and the dimensions of the radiator, are most significantly expressed in wave lengths, too. For example, the dipole arrangement of Fig. 20 is a very effective radiator if it is one-half wave in length. At 60 c.p.s. this would mean a length of $\frac{3 \times 10^8}{2 \times 60} = 0.25 \times 10^7$ meters $= 0.25 \times 10^4$ kilometers or 1,500 miles! Such a length is obviously impractical, and also the ohmic losses in such a line would be far too excessive. On the other hand, the dipole for a 300-mc. wave would have to be only 0.5 meter long--a very practical value. But the dipole for a 10,000-mc. wave would have to be 1.5 cm. long, and this is now somewhat short for a practical construction. Indeed, at these so-called microwave frequencies the technic has to be modified because dimensions begin to be uncomfortably small. Another factor to be noted is that the *radiation losses* of ordinary coils and condensers begin to become appreciable and even excessive as one gets into the 300-mc. range. Fields that were essentially of the closed type at the lower frequencies begin to be open at these higher frequencies.

It will be of value to classify radio waves and other electromagnetic waves of higher frequency in order to understand how radio waves compare with heat, light. X-rays, etc. The following table has therefore been prepared to present this information:

Frequency	λ	*Designation*
10 -- 30 kc.	30,000 -- 10,000 meters	Very low frequencies*
30 -- 300 kc.	10,000 -- 1,000 meters	Low frequencies*
300 -- 3,000 kc.	1,000 -- 100 meters	Medium frequencies*
3,000 -- 30,000 kc. (30 mc.)	100 -- 10 meters	High frequencies*
30 -- 300 mc.	10 -- 1 meters	Very high frequencies*
300 -- 3,000 mc.	1 meter -- 10 cm.	Ultra-high frequencies (u.h.f.)*
3,000 -- 30,000 mc.	10 cm. -- 1 cm.	Super-high frequencies*
2.4×10^{6} -- $.43 \times 10^{9}$ mc.	125 mm. -- 7,000 A.**	Infra-red
$.43 \times 10^{9}$ -- $.75 \times 10^{9}$ mc.	7,000 A. -- 4,000 A.	Visible spectrum (light)
$.75 \times 10^{9}$ mc. and up	4,000 A. --	Ultra-violet
2×10^{10} -- 3×10^{11} mc.	150 A. -- 10 A.	X-rays
1.14×10^{12} -- 3×10^{20} mc.	1.40 A. -- .010 A.	Gamma Rays (from radium)
6×10^{21} mc.	.0005 A.	Cosmic Rays (Celestial origin)

(*) The above designations were adopted by the F.C.C. early in 1940.

(**) These wave lengths are so short that they are expressed in Angstrom units. An Angstrom is equal to 10^{-8} cm.

Although .4 mm. is given as the longest infra-red wave length, actually there is no limit to the wave length, since infra-red merely means *below the red* color in frequency. However, .4 mm. is about the shortest wave artifically produced by other than electrical means. Also, radio waves as short as .22 mm. have been produced by electrical oscillators, but are not as yet of practical importance. The student is referred to an interesting article by Dr. G. C. Southworth entitled "Beyond the Ultra-short Waves" which appeared in the *I.R.E. Proceedings* for July 1943, where these matters are further discussed.

It may puzzle the student why radio waves--particularly in the broadcast band--appear to behave differently from light waves: why, for instance they can penetrate brick buildings, sweep around obstructions (which apparently cast no shadows for radio waves) and be generated in a cold conductor by alternating currents. instead of by incandescent bodies.

The reason is that it is simply a matter of wave length. It is a general law in wave motion that an object comparable to or larger than the wave length acts as a reflector to the wave incident upon it, and casts a shadow behind it. An object small compared to a wave length does not appreciably reflect the wave motion, and does not cast an appreciable shadow behind it because the wave can *diffract* or sweep around this relatively small obstruction. An examination of the table on page 38 shows that the frequency *range* of the visual portion of the spectrum is less than an octave (2 : 1 ratio). Over such a small range very little difference in behavior can normally be noted, although red light can diffract around and hence pass through a smoky atmosphere better than violet light can, as the smoke particles may be of just the right size appreciably to reflect the latter waves.

In the same way, broadcast waves (in the order of 500 meters) can sweep or diffract around ordinary size obstructions, such as steel buildings, whereas at television frequencies--50 mc. and up--troublesome reflections begin to occur at television receivers located in the vicinity of large buildings, particularly if the building is in front of the receiver and in line with the television transmitter.

The principle of reflection of very short radio waves is made use of in the most important war radio development, radar. In a similar manner it makes possible the absolute altimeter or "terrain indicator" by which the height of an airplane above the nearest object below--ground, tall buildings. etc.--is indicated.

Short radio waves begin to exhibit more closely the properties of light: they are transmitted over "line-of-sight" paths to the horizon, and are said to exhibit *quasi-optical* properties. Microwaves, for example, can be transmitted through hollow pipes and insulators.

Maxwell showed that insulators are transparent to electromagnetic waves--even light waves. However, there are qualifying considerations, such as the presence of conducting impurities in the insulator, that are small compared to the longer radio waves but large compared to light waves, and which absorb the latter inside the insulator by multiple reflections. But it is evident that there is no *basic* difference between the two.

Parabolic reflectors for light waves are generally thousands of times as large as the wave length of the light, and can therefore concentrate the beam in a very small angle. Reflectors of much the same form and reasonable size can and are used for the shorter radio waves. In general, it is much easier to confine ultra-short radio waves in a narrow beam than the longer waves. Yet the latter can be made fairly directive by employing the principle of wave interference, upon which any directional light reflector really operates, in a simpler and somewhat cruder manner: by the use of auxiliary wire structures or antennas, driven either from the main antenna (parasitic excitation) or directly from the transmitter.

Light waves can be refracted (bent) in passing from one medium to another that has a different index of refraction. This is the principle upon which the optical lens operates. In a similar manner the radio wave is refracted as it passes through differently ionized layers of the earth's atmosphere. It is by virtue of this property that radio waves can be picked up suddenly at surprisingly great distances ("skip distances"). The effect of refraction increases with wave length so that the bending effect is greater at the longer wave lengths than at the shorter wave lengths. The effects of this on radio communication will be shown in a following lesson.

Finally, in attempting to radiate light frequencies by alternating currents, one finds that the displacement of the electrons is so small that they are substantially interatomic vibrations. These are produced more readily by heat agitation, as in the incandescent lamp, or by atomic bombardment, as in the more recently developed fluorescent light. Radio waves, on the other hand, are more readily generated by the larger excursions of the free electrons through an ordinary circuit.

RADIATION RESISTANCE.--As was shown previously, the energy radiated represents a loss of energy from the system--a power conversion, in other words--that can be measured by conventional methods just as the amount of energy converted into heat and dissipated in the ohmic resistance of the radiator conductors can be measured. From this is developed a term "radiation resistance" which will be discussed in greater detail later. At this point it suffices to state that it is an equivalent resistance which, when inserted in series with an antenna system that is not permitted to radiate, consumes the same amount of energy from the source as the antenna system does when permitted to radiate.

Another apparent resistance which the generator may see when feeding the antenna is that due to losses from nearby conducting objects. These can be coupled to the antenna through the inductive field, like the secondary of a transformer is coupled to the primary, for example. The losses in such objects represent energy extracted from the induction as well as from the radiation field. The latter loss is already included in the radiation resistance, since it is immaterial to the source whether it loses energy into space in general, or to some object in space at one concentrated location. But the energy extracted from the induction field is energy that also will not be retrieved by the source. Such loss must be represented by another equivalent resistance inserted in series with the antenna.

However, this loss can be minimized if such absorbing objects are kept relatively far away from the radiator. It will be recalled that the induction field varies inversely as the square of the distance. At a distance of several wave lengths it may be considered negligibly small, and thus objects located at such distances and beyond will have negligible effect upon the radiating system, and but local effect upon the radiation field pattern. This matter is important in determining the location and design of a radiating system.

POLARIZATION.--It will be recalled that the electric and magnetic lines of the radiation field are perpendicular to one another and to the direction of their motion. *The direction of the electric field lines is* *by definition called the polarization of the wave.* Thus, if these field lines are vertical at the point of observation, the wave is said to be vertically polarized; if horizontal, it is said to be horizontally polarized. At different points in space the wave may be differently polarized, but for certain special forms of antennas and antenna arrays it is possible to have the electric field vector, at all points where there is radiation, point always in the same direction: for example, horizontally with respect to the earth's surface. Such a wave is said to have pure polarization.

REFLECTION.--When an electromagnetic wave strikes a perfect conductor of sufficient length to be an antenna in itself, and arranged *parallel* to the direction of the polarization, voltages and currents will be set up in the conductor. The currents will cause radiation from the conductor, and so some of the energy will be sent back toward the source, as well as some out in the same direction as the original energy. The energy sent back toward the source represents a reflection of the incident energy. If the object is not a perfect conductor it will absorb some of the incident energy and the reflection will be less. It is important to note that the reflection is essentially a *reradiation* of the intercepted energy.

Reflection can occur from the earth's surface. Horizontally and vertically polarized waves are reflected to a different degree and with different results by the earth. For example, in aeronautical engineering it has been found that horizontally polarized waves are less affected by reflection from the earth than vertically polarized waves, and are therefore now being employed for localizer courses and glide paths for instrument landing systems.

In general, reflection occurs whenever the electromagnetic wave attempts to pass from one medium into another. A certain amount of energy from the wave is reflected; a certain amount penetrates and proceeds in the second medium, usually in a direction not in line with that in the first medium. This bending of the transmitted wave is called *refraction*.

The amount of reflection depends mainly upon the *conductivities*, the *permeabilities*, and the *dielectric constants* of the two media, and on the frequency of the wave.

The condition for no reflection between two media can be very simply expressed if neither medium has any conductivity (is an insulator) and has no dielectric nor magnetic losses. The condition is that

$$\frac{\mu_1}{\varepsilon_1} = \frac{\mu_2}{\varepsilon_2}$$

where μ_1 and ε_1 are the permeability and dielectric constant of the first medium, and μ_2 and ε_2 the corresponding values for the second medium. This condition is not usually satisfied by most media in that for most the permeability is one, and the dielectric constants are different. For,example, at ultra-high frequencies the earth may be regarded as a dielectric having a value of ε considerably greater than unity, whereas ε for air is practically unity. Hence, an electromagnetic wave proceeding from an antenna above the earth to the earth is reflected from the latter almost completely. This modifies the radiation pattern of the antenna markedly, as will be discussed later.

In the case of a metal, the conductivity must be taken into account (as well as its permeability if it is iron or nickel, or the like), but the *dielectric constant can be taken as zero.* If these factors and those for air are inserted in the rather involved formula for reflection, it will be found that the reflection is also about 100 per cent, i.e., a metal, as indicated previously, is practically a perfect reflector under normal conditions.

ELECTRICAL CHARACTERISTICS OF AN ANTENNA.--It has been indicated that for an antenna to radiate appreciably its fields must be "open" and as a result the antenna dimensions should be comparable to the wave length of the radiated energy. For example, a vertical antenna operating on 30 mc. may be 2.5 meters long (about 8.2 feet). The length of the radiated wave is

$$\lambda = \frac{3 \times 10^8}{3 \times 10^7} = 10 \text{ meters}$$

so that the antenna is 2.5/10 = $\lambda/4$. A quarter-wave length antenna is quite common, and antennas a half-wave in length are used to a large extent at the higher frequencies in the form of dipoles. On the other hand, a quarter-wave vertical antenna for a frequency of 300 kc. would have to be

$$\frac{3 \times 10^8}{4 \times 3 \times 10^5} = 250 \text{ meters} = 820 \text{ feet long}$$

which is an uneconomical height, particularly for a small, low-power installations. In such a case a much shorter antenna would be used.

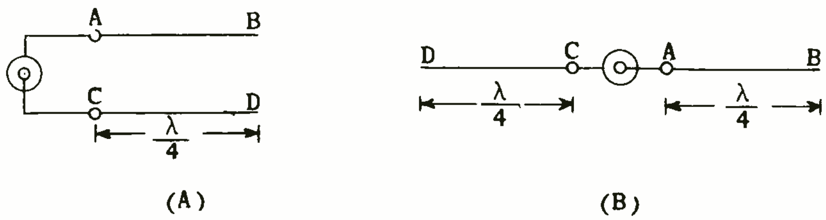
Circuits such as the above antennas, that are comparable to the wave length of radiant energy in free space at the operating frequency are known as *electrically long* circuits, and belong to the class of transmission lines. They can no longer be considered as consisting of concentrated or lumped portions of inductance, resistance, and capacity connected together in certain definite configurations; instead, these circuit constants are *distributed* usually uniformly throughout the space occupied by the circuit. For example, a half-wave dipole consists of two wires extending in opposite directions from the source, and each one-quarter wave long. The source alternately pulls electrons out of one wire and into the other, and then from the latter into the former, at a rate corresponding to its frequency. The resultant current flow charges up the two conductors like the plates of a condenser, but at the same time sets up magnetic flux around the conductors. The circuit thus exhibits in addition to a capacitive reactance an inductive reactance, and the two effects are distributed throughout the system. This is characteristic of a transmission line.

The behavior of such an antenna or any transmission line is in many respects different from that of circuits having lumped constants such as coils and condensers although the same fundamental laws--such as those of Ohm and Kirchoff--apply to either. For example, if the line is more than a half-wave in length, the current at any instant *beyond* the first half-wave portion may flow in a direction opposite to that *within* the first half-wave portion! This seems paradoxical and contrary to the application of Kirchhof's law to a series circuit, which indicates that the current is everywhere the same. The explanation is that the current that flows out of the source into one of the wires represents the *total* charging current for the capacity of that wire to the other wire. As one proceeds along the wire, more and more current is diverted as charging current, and less and less is available to the remaining portion of the wire. Later on in the cycle the currents reverse and the two wires charge up in the opposite direction. But if the wires are each long enough relative to the frequency, one portion may be discharging while the other portion is charging, and give rise to opposite current flows in the two portions of the same wire.

This is an important point, because the radiation from one portion will cancel that from the other portion in certain directions, and the directional pattern of radiation from that antenna will depend upon this action as well as the difference in path lengths from the various parts of the antenna to the point in question. However, for antennas that are less than $\lambda/2$ in length, the current will be everywhere in the same direction, but the electrical characteristics of the antenna will still be an important factor in its behavior. To understand this some properties of transmission lines must be presented, although transmission lines will be covered much more thoroughly in later lessons.

A line that is open- or short-circuited at its far end exhibits certain resonance phenomena owing to the standing waves set up on it by interaction between the outgoing wave and the wave reflected from the far end. (While it is simpler to study the transmission line as a circuit problem, it is actually a wave phenomenon and represents radiation that is *guided by the wires around a restricted path*, except for the radiation that escapes and makes the particular transmission lines studied here antennas as well as lines.) Specifically, a quarter-wave, open-circuited line looks like a series resonant circuit to the generator feeding it. The inductive and capacitive reactances in the line balance one another, so that the generator voltage can force a large current through the antenna. The current is limited solely by the resistance of the circuit, and is therefore relatively large, since the resistance is usually small and is composed of ohmic losses, radiation losses, dielectric losses and the like, none of which is very large.

At this point it is well to note that the length of the usual two-wire transmission line refers to the transmission distance. The actual total length of conductor is twice this length. If one of the conductors is turned around until it faces in the opposite direction, as in the case of the dipole antenna, then the actual length of the latter is twice the ordinary transmission line length. For example, in Fig. 22 a dipole made up of two quarter-wave lengths of wire, totalling a length of one-half wave, acts



Transformation of a two wire quarter-wave transmission line (A), into a dipole half-wave antenna (B).

Fig. 22

electrically like a quarter-wave line when fed in the center. But the *radiation resistance* is that of a *half-wave line*. This should be remembered while studying the material that is to follow.

For antennas shorter than a quarter-wave in the case of a grounded single wire antenna, or half-wave in the case of a dipole antenna, the impedance becomes predominantly *capacitive*, just like any series resonant circuit operated at a frequency below resonance. The capacitive reactance becomes very high compared to the resistance as the frequency is lowered for a given antenna--or alternatively, the antenna is shortened for a given frequency--and the current is limited in such a case almost solely by the capacitive reactance rather than by the resistance.

On the other hand, if the frequency is raised, or the antenna lengthened, so that the antenna is longer than a quarter-wave, the impedance changes to an *inductive* reactance of high value, and again this, rather than the resistance of the circuit, limits the current flow. In either case a small change in length or frequency produces a large change in reactance, or the system behaves like a series resonant circuit of high Q (low losses). This indicates that, except at resonance, the radiation resistance has very little effect upon the current flow *unless means are employed to cancel out the associated reactance.*

The above remarks concerned the series resonance of a quarter-wave antenna. When the antenna is a half wave in length as a transmission line (full wave as a radiator), it again exhibits resonance, but this time *parallel* resonance. The impedance looking into such a circuit is now very high, although resistive in nature, and composed of the same components as before. (If it were not for this resistance the impedance would appear infinite.) Beyond a half-wave length the antenna appears capacitive once more until 3/4 λ is reached, when it is again in series resonance. From then on it appears as an inductive reactance until a full wave length is reached, when it appears anti-resonant (parallel resonant) once more. The same alternation in impedance continues for further increase in antenna length.

An important point is that the radiation resistance depends not on the actual length, nor on the frequency, but upon the *relative length* of the antenna in *fractions of a wave length.* For an antenna isolated in free space the radiation resistance varies with wave length as shown in Fig. 23. Specifically, a quarter-wave antenna has a radiation resistance of 36.57 ohms; a half-wave, 73.2 ohms, etc. This value of resistance, when multiplied by the square of the *maximum effective* value of the antenna current, gives the power radiated.

The expression maximum effective value of the antenna current requires explanation. Mention was made previously that the current in a long antenna may flow in opposite directions in the several portions of the antenna. It is evident that if the current in one portion flows in one direction, and that in the next portion flows in the opposite direction, somewhere in between the current flows in neither direction, i.e., it is zero. Such points on the antenna (or, in general, on a transmission line) are called current nodes. Halfway between these current nodes are points where the current is a maximum. These are called current antinodes. It must not be thought by the student that the current at the antinodes is constant in value with time: it alternates with time, but its *peak* value *and r.m.s.* or *effective* value are a maximum here. It is the *effective* value of the current at such an antinode that is to be squared and multiplied by the radiation resistance to give the radiated power.

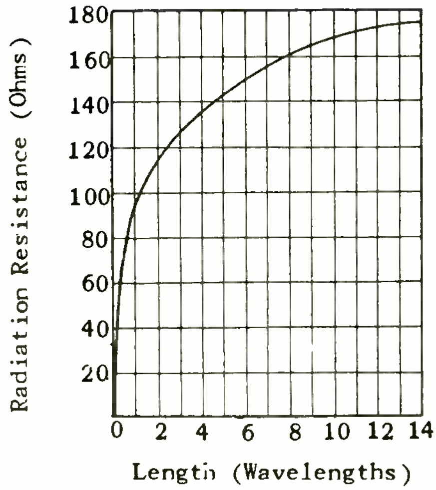


Fig. 23

More will be said later about the antenna current distribution, but at this point it is desired to call the student's attention to the fact that if the antenna can be made long enough, it can radiate just as effectively at low frequencies as a shorter length can radiate at high frequencies! This may seem to contradict the remarks made earlier in the lesson to the effect that radiation was greater at higher than at lower frequencies. However, that statement was based on the assumption *that the current in all parts of the radiating system was the same*, whereas in actual antennas *phase differences* in the current up to 180° (currents flowing in opposite directions) and higher occur *because of the distributed nature of the circuit constants*. In the simple examples given earlier this characteristic was purposely not considered as it would have complicated the discussion. Another factor not considered, but important in practice, is the directivity of the antenna.

Nevertheless, the remarks made then were essentially correct. Note, from Fig. 23, that in spite of the transmission line properties of the antenna, its radiation resistance *does* increase with its length in waves, i.e., with *frequency* if its *length* is *maintained constant*, or with *length*, if the *frequency* is *kept constant*.

This brings out an important point in the feeding of an antenna. Suppose an antenna much shorter than λ/4 has to be employed. Electrically it looks like a small condenser (high capacitive reactance, X_c) in series with a very small resistance. Assume for the moment that there are no losses except that of radiation. Then the total resistance will be simply the radiation resistance R_a, and this may be as little as five ohms (or less), if the antenna is short enough. The total impedance will be

$$Z = \sqrt{(X_c)^2 + R_a{}^2} \cong X_c$$

since X_c is so much greater than R_a. But now suppose a suitable coil is placed in series with the antenna, and of such inductance that its reactance, X_L is just equal (and opposite) to X_c. The two reactances will balance one another (resonance), so that the net impedance to the generator will now be R_a, or about 5 ohms. Presumably a large current can now flow, and a reasonable amount of radiation can be had, even though the antenna is relatively short and consequently a poor radiator.

Theoretically this is true. Theoretically an antenna 100 feet high could radiate a large amount of power at 60 cycles if its tremendously high capacitive reactance could be cancelled out, and an enormous current be forced to flow into it. It is evident that this example indicates difficulties in practice. In the first place, a coil of enormous inductance would be required to balance the tremendously high capacitive reactance. Such a coil would not only be exceedingly large and costly, but perhaps radiate more readily than the 100-foot antenna, and it would undoubtedly have such a high ohmic resistance as to waste far more power than would be radiated, since the radiation resistance would be very small fraction of an ohm. Furthermore, it would be exceedingly difficult, if not impossible, to build such a large coil that would not have excessive distributed capacity.

The second difficulty has to do with the attempt to obtain such a high current flow. The source would have a certain internal resistance. For optimum results, the load resistance as it appeared across the source terminals would have to have a value of the same order of magnitude to obtain any reasonable power output and efficiency. Suppose the value was 2 ohms, and the actual radiation resistance was .0001 ohm. Then a step-down transformer of turns ratio

$$n = \sqrt{\frac{2}{.0001}} = 141.4 : 1$$

would be required. At 60 cycles this might be feasible, but in the usual r.f. range it would not be.

At the higher radio frequencies the load resistance, such as the radiation resistance of the antenna, is coupled to the source of power by means of a circuit as shown in Fig. 24. Here L_t is the primary of an air core transformer, tuned by C_t to be parallel resonant at the frequency of the source. L_c is the Secondary of this transformer, and can be moved with respect to L_t so as to link more or less of the magnetic flux set up by L_t. This is called varying the *coupling*. L_a is the inductance used to cancel out the reactance of the antenna capacity, C_a. (Generally the self-inductance of L_c, in conjunction with L_a performs this cancelling or series-tuning effect.) Finally R_a is the radiation resistance.

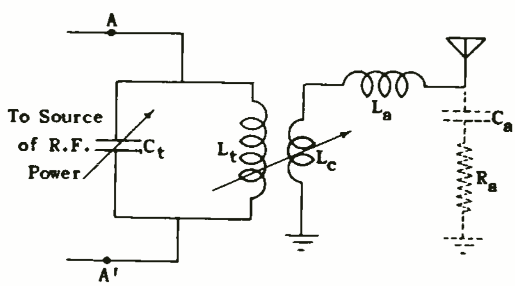


Fig. 24

If the antenna is very much less than λ/4, both R_a and C_a are very small. It is the function of the coupling adjustment to make R_a (the net impedance of the secondary circuit after tuning has been accomplished) appear as the proper resistance across terminals AA' to draw maximum power from the source. If R_a is very small then the coupling must be made very weak, i.e., L_c must be moved relatively far away from L_t so as to link very little of its flux. The difficulty in this is that stray magnetic flux from L_t which links some conducting material in the region may reflect the resistance of this conductor across AA' as a value comparable to the reflected value of R_a, so that as much power will be wasted in structural members of the equipment as is delivered to the antenna.

As a result of the above difficulties in attempting to couple a relatively short antenna to the source, no attempt is made to operate at frequencies below 10,000 c.p.s., but above this frequency, particularly from about 500 kc. on, radiation can be obtained about as efficiently at one frequency as another since antenna lengths approaching $\lambda/4$ are feasible. The choice of frequency depends on other properties of the particular electromagnetic wave rather than its ability to be radiated. However, even frequencies just above the standard broadcast band difficulties are encountered in radiating energy from the necessarily short antennas used with police car transmitters and in airplanes. In the latter case a long trailing antenna is often employed to obtain a higher radiation resistance.

Up to a few years ago antenna design was quite simple. The antenna was supported between two towers which were spaced to permit a fairly long flat top (to be discussed later). The principal precaution was to ensure that the fundamental wave length was slightly below the desired operating wave length, so that a reasonably small amount of inductive loading could be used for coupling. If the antenna fundamental wave length were too long, so that it had an inductive instead of capacitive reactance, it could be "shortened" by means of a series capacity. In some cases such as with shipboard antennas, where the height, length and shape are largely determined by existing supporting structures, and where a fairly wide band of frequencies must be covered with a single antenna, such "rule of thumb" design is still used to some extent.

In the broadcast and associated fields, however, where permissible power output is restricted and where it is essential to deliver the strongest possible signal--consistent with the power limitation--into the desired area, a great deal of research has gone into antenna design, including that of directional arrays. The principal features of design of a vertical radiator are its shape and height, because these factors determine the form of current distribution over the structure and hence the shape of the vertical radiation field pattern.

After the antenna has been constructed it is often necessary to couple it to a transmitter through a *transmission line*. In order to design the coupling circuit between the transmission line and the radiator, *usually an impedance matching filter*, it is necessary to know *both the reactance and the resistance* of the antenna at the frequency at which it is to be operated. As was mentioned before, if it is less than a quarter-wave

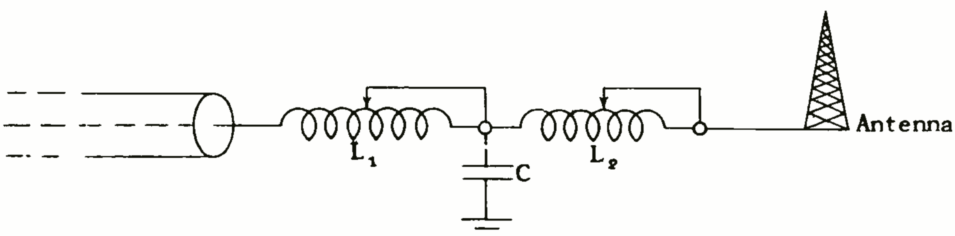


Fig. 25

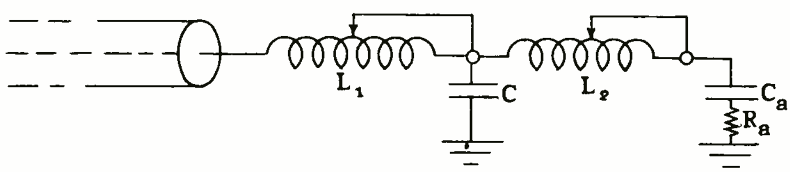


Fig. 26

length it appears as a condenser and resistance in series. A more elaborate antenna coupling circuit is shown in Fig. 25, and the equivalent circuit in Fig. 26. This coupling circuit is of the so-called Tee configuration, from its resemblance to the letter T, and it cancels out the reactance of C_a and also transforms R_a into the proper value to terminate the transmission line in its so-called characteristic or surge impedance Z_o. The line then functions in the optimum manner. Before the coupling network can be designed R_a, C_a, and Z_o must be known.

All of these values may be measured by means of an r.f. impedance bridge. Such a bridge is designed to measure Z in terms of both R and X and to indicate whether X is positive or negative, that is, inductive or capacitive. In most cases of conventional design X_a will be negative and hence L_2, the loading component of the filter, will be required.

Usually in making antenna measurements with an impedance bridge a series of measurements will be made and curves of R_a and X_a will be plotted to show these values over a range of frequencies on both sides of the normal operating frequency. At any frequency at which X_a is negative, the coupling circuit facing the antenna must be inductive in order to cancel the negative (capacitive) reactance and resonate the antenna circuit. If it is desired to operate the antenna at a frequency at which X_a is positive, L_2 would be replaced by a series condenser having the required capacitive reactance at the operating frequency to cancel the positive reactance of the antenna. The necessary calculations for the design of suitable coupling and impedance matching circuits are discussed in another lesson.

RADIATION AND RADIATORS

EXAMINATION

1. What portions of the electric field lines represent the radiation electric field? Explain briefly.

2. (a) What are the relative positions in space of the *radiation* electric and magnetic fields?

   (b) What are the relative positions in space of the *induction* electric and magnetic fields?

   (c) What is the time phase between the radiation electric and magnetic fields?

   (d) What is the time phase between the induction electric and magnetic fields?

3. (a) What is the direction of flow of the radiant power with respect to the directions of the radiation electric and magnetic fields?

   (b) How is this represented, and what is it called?

4. (a) How does either radiation field intensity vary with distance from the source?

   (b) How does either induction field intensity vary with distance from the source?

   (c) Where are they equal in intensity?

5. What is an open field, and how does it affect radiation? Give an example of an open field.

6. What is radiation resistance? How does it differ from ohmic resistance in the conductors comprising the antenna?

7. (a) How does a horizontally polarized wave differ from a vertically polarized wave?

   (b) What is the essential characteristic of reflection?

   (c) What two characteristics of two insulating media determine reflection at their common boundary?

8. (a) What is the wave length in meters corresponding to a frequency of 27 mc.?

   (b) What is the frequency corresponding to a 20-cm. wave?

9. Why is it difficult to radiate from an antenna that is much less than $\lambda/4$ at the operating frequency? Explain in detail.

10. How is the type of loading (tuning) for an antenna determined?