

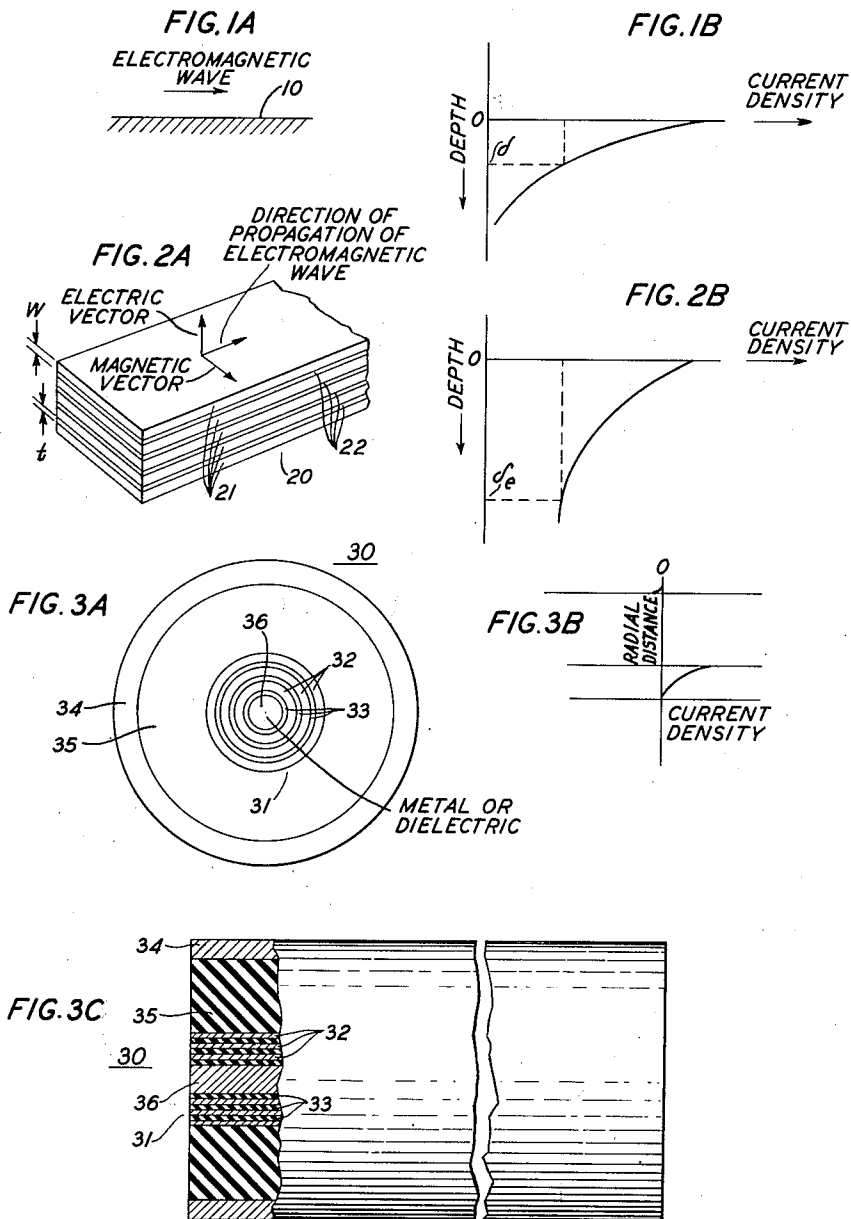
Oct. 30, 1956

A. M. CLOGSTON
COMPOSITE ANTENNA STRUCTURE

2,769,170

Filed May 29, 1952

5 Sheets-Sheet 1



INVENTOR
A. M. CLOGSTON

BY

Hugh S. Wentz
ATTORNEY

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FIG. 3D

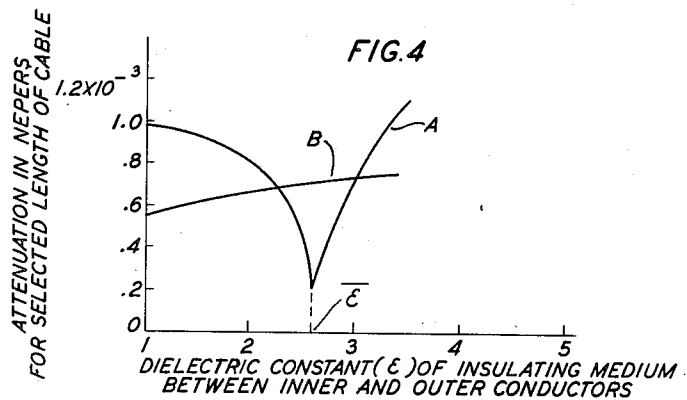
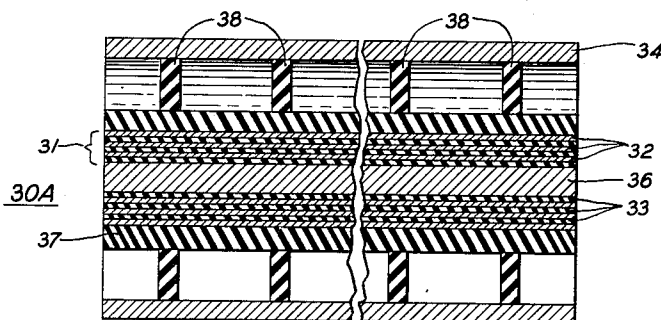
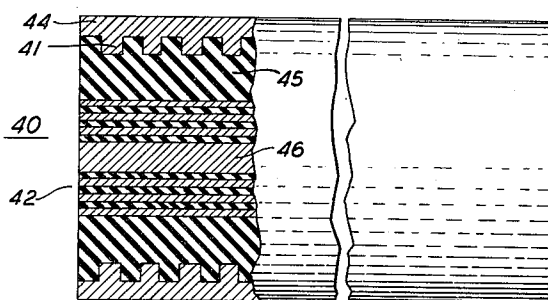


FIG. 5



INVENTOR
A. M. CLOGSTON

BY *Hugh S. Wertz*
ATTORNEY

Oct. 30, 1956

A. M. CLOGSTON
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FIG. 6

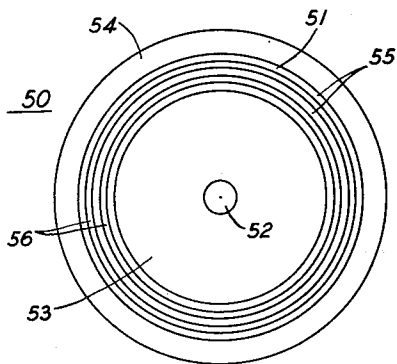


FIG. 7A

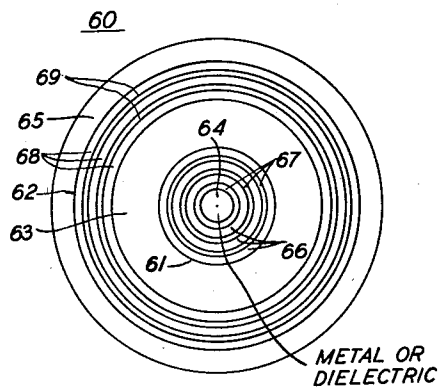


FIG. 7B

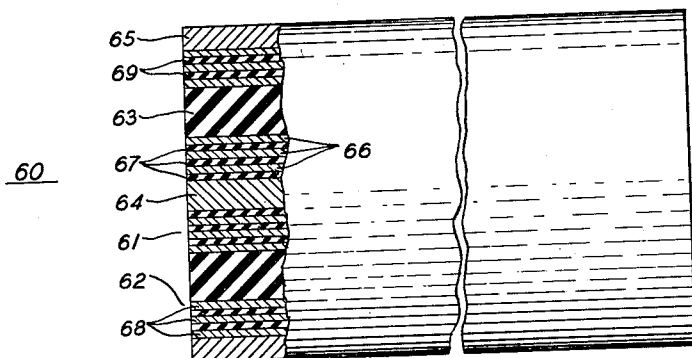
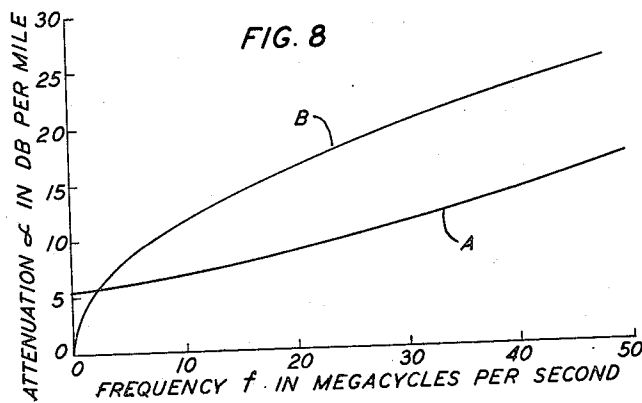


FIG. 8



INVENTOR
A. M. CLOGSTON

BY

Hugh S. Wertz

ATTORNEY

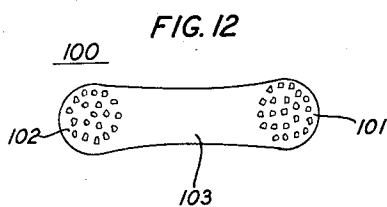
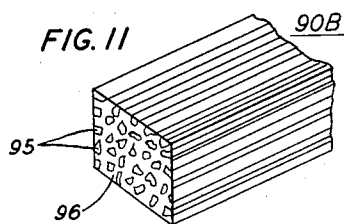
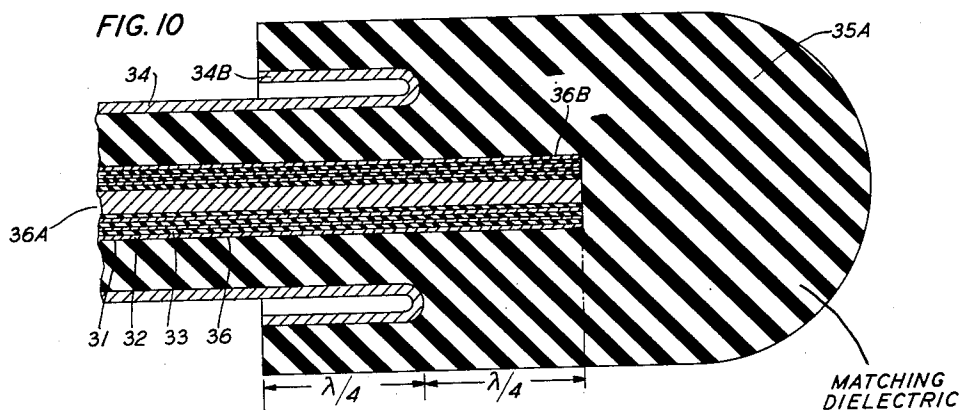
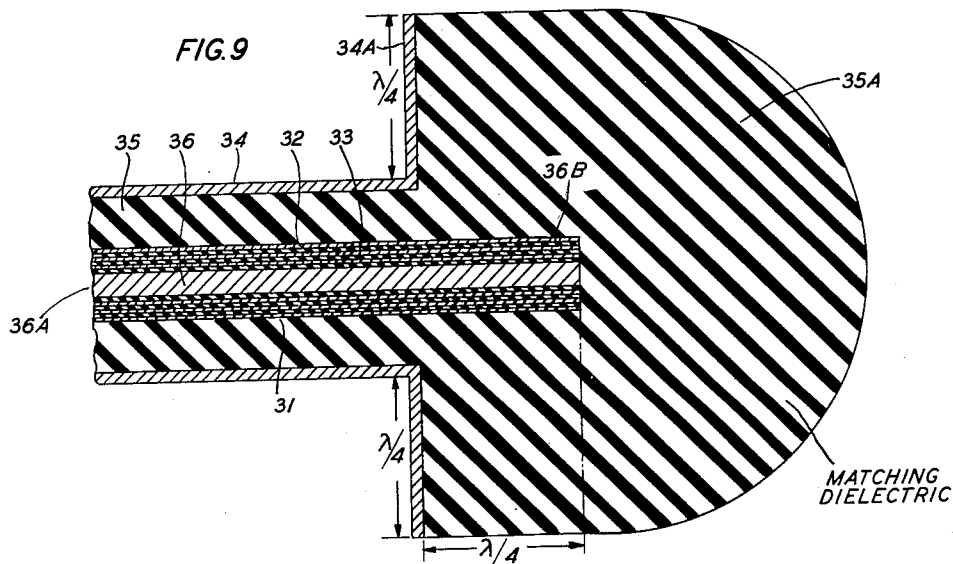
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A. M. CLOGSTON
COMPOSITE ANTENNA STRUCTURE

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INVENTOR
A. M. CLOGSTON
BY *Hugh S. Warty*
ATTORNEY

Oct. 30, 1956

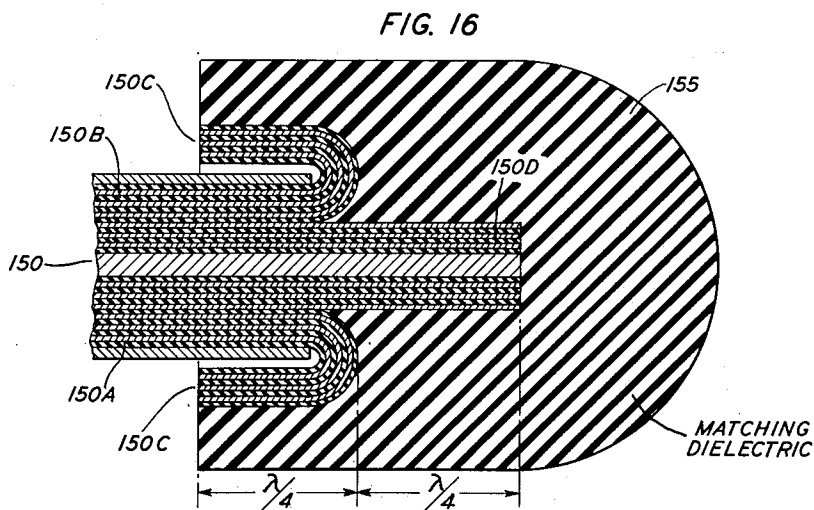
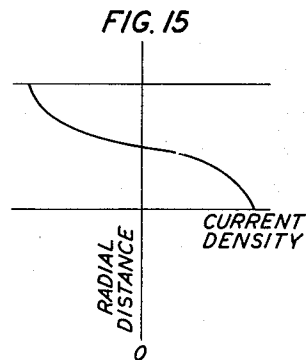
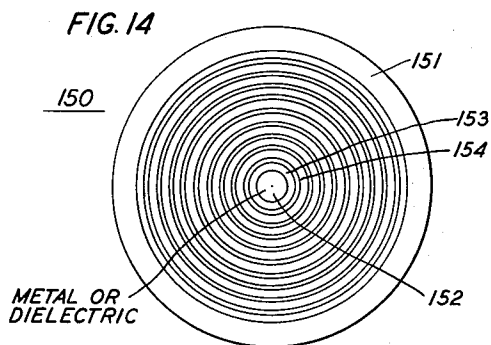
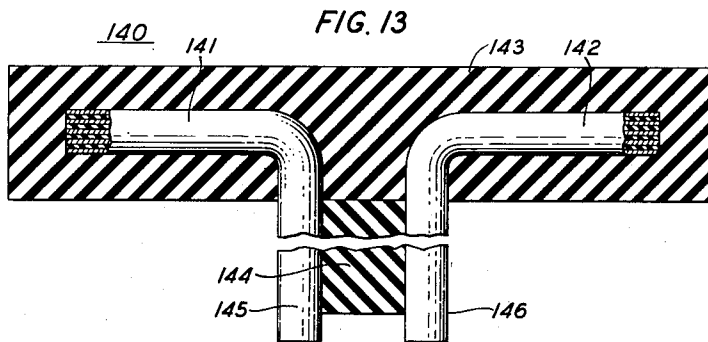
A. M. CLOGSTON

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COMPOSITE ANTENNA STRUCTURE

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5 Sheets-Sheet 5



INVENTOR
A. M. CLOGSTON

BY

Hugh S. Wentz

ATTORNEY

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2,769,170

COMPOSITE ANTENNA STRUCTURE

Albert M. Clogston, Morris Plains, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application May 29, 1952, Serial No. 290,805

13 Claims. (Cl. 343—907)

This invention relates to antennas and has as one of its principal objectives the improvement of antennas with respect to "skin effect." This application is a continuation-in-part of application Serial No. 214,393, filed March 7, 1951.

Due to the phenomenon known as "skin effect," at high frequencies the current distribution through a conductor is not uniform. Consider, for example, the case of a two-conductor coaxial line to which are applied waves of increasing frequency. At zero and sufficiently low frequencies the currents in the conductors are substantially uniformly distributed throughout and the resistance of the conductors and hence the conductor loss in the line is at a minimum. With increasing frequency the current distribution changes so that the current density is a maximum at the inner surface of the outer conductor and at the outer surface of the inner conductor and decreases into the material at a rate depending on the frequency and the material. In the example given the current density may be negligible at the other surface of each conductor. From another point of view, the electromagnetic field between the two conductors (where the useful power is transmitted) penetrates into the conductors with a field intensity decreasing with distance. Thus the current density (or field) in each conductor is associated with a power loss that is a function of the distribution of current density (or field) across the thickness of the conductor.

It is thus a more particular object of this invention to reduce the power loss associated with skin effect in electrical conductors and particularly to conductors utilized in antenna systems.

Further objects of the invention are to reduce the extent to which the power loss in such a conductor varies with frequency, and to make such power loss and consequently its contribution to the attenuation of an antenna made up of such conductors substantially independent of frequency over a broad band of frequencies from the lowest frequency of interest to the highest. For example, in practice, such a band might be comparatively narrow or alternatively might be sufficiently wide as to accommodate a plurality of wide-band television channels.

This invention, in one of its more important aspects, resides in a composite electrical conductor for antennas that is separated, transverse to the direction of desired wave energy propagation, into a multiplicity of insulated conducting elements of such number, dimensions and disposition relative to each other and the orientation of the electromagnetic wave as to achieve a more favorable distribution of current and field within the conducting material.

In the case of the two-conductor coaxial line, one or both of the conductors is formed, in accordance with the invention, of a multiplicity of thin metal laminations insulated from one another by layers of insulating material, the smallest dimension of the laminations being in the direction perpendicular to both the direction of wave

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propagation and the magnetic vector. A convenient yardstick in referring to the thickness of the metal laminations and of the insulating layers is the distance δ given by

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \quad (1)$$

where δ is expressed in meters, f is the frequency in cycles per second, μ is the permeability of the metal in henries per meter, and σ is the conductivity of the metal in mhos per meter. The factor δ measures the distance in which the current or field penetrating into a slab or the metal many times δ in thickness will decrease by one neper; i. e., their amplitude will become equal to $1/e = 0.3679 \dots$ times their amplitude at the surface of the slab.

This factor δ will be called one skin thickness or one skin depth. In the case being considered, it is contemplated that the thickness of each lamination is many times (for example, 10, 100 or even 1000 times) smaller than δ (in general, the thinner the better) and that there will be many laminations (for example, 10, 50, 100 or more). It has been found that when the conductor has such a laminated structure, a wave propagating along the conductor at a velocity in the neighborhood of a certain critical value will penetrate further into the conductor (or completely through it) than it would penetrate into a solid conductor of the same material. This results in a more uniform current distribution in the laminated conductor and consequently lower losses. Another way of looking at this result is to say that the "effective skin depth" is much larger in the laminated conductor than the skin depth δ for a solid conductor of the same material as the laminations.

The critical velocity mentioned above is determined by the thickness of the metal and insulating laminae, and the dielectric constant of the insulating laminae. The electromagnetic wave can be caused to propagate in the neighborhood of this critical velocity by a variety of means including (for example) the proper disposition of dielectric material in the vicinity of the conductor. By way of example, in one form of coaxial cable which is utilized in an antenna system constructed with the invention, that is, in the case of two laminated concentric conductors (each comprising a multiplicity of metal laminae thin compared to δ separated by thin insulating layers) which are separated from each other by a main dielectric, the wave propagates at the critical velocity if the dielectric constant of the main dielectric is given by

$$\epsilon_1 = \epsilon_2 \left(1 + \frac{W}{t} \right) \quad (2)$$

where ϵ_1 is the dielectric constant of the main dielectric element between the two conductors in farads per meter, ϵ_2 is the dielectric constant of the insulating material between the laminae of the conductors in farads per meter, W is the thickness of one of the metal laminae in meters, and t is the thickness of an insulating layer in meters. The insulating layers are also made very thin and an optimum thickness for certain types of structures in accordance with the invention (as will be described more fully below) is that in which each insulating layer is one-half of the thickness of a metal lamina.

The principles of the invention are not limited to laminations but are applicable also to filaments. Moreover, in certain circumstances, the laminations or filaments need not be continuous, as breaks therein will not cause the conductor to be inoperative at high frequencies.

The invention will be more readily understood by referring to the following description taken in connection with the accompanying drawings forming a part thereof, in which:

Fig. 1A is a schematic representation of an electro-

magnetic wave propagating through space in the neighborhood of an electrical conductor;

Fig. 1B is a graph of current density vs. depth (distance away from the surface) in the conductor of Fig. 1A;

Fig. 2A is a schematic diagram showing respectively the directions of electric and magnetic field vectors and the direction of propagation of an electromagnetic wave near the surface of a composite conductor in accordance with the invention;

Fig. 2B is a graph having the same coordinates as in Fig. 1B, and showing the increased skin depth produced by the conductor of Fig. 2 as compared with that of Fig. 1A;

Fig. 3A is an end view of a coaxial transmission line which is utilized in various forms of antennas in accordance with the invention, the inner conductor of the line comprising a multiplicity of metal laminations insulated from one another and the inner and outer conductors being separated by dielectric material;

Fig. 3B is a diagrammatic representation showing the distribution of current in the inner and outer conductors of the embodiment shown in Fig. 3A;

Fig. 3C is a longitudinal view, with portions thereof in section, of the embodiment shown in Fig. 3A, a continuous dielectric being used between the inner and outer conductors;

Fig. 3D is a longitudinal cross-sectional view of a section of a cable of the type shown in Fig. 3A, except that the dielectric material between the inner and outer conductors only partially fills the space therebetween;

Fig. 4 is a graph of attenuation vs. dielectric constant of the insulating medium between the inner and outer conductors of (A) a coaxial cable of the type shown in Fig. 3A and (B) a coaxial cable of a conventional type;

Fig. 5 is a longitudinal view, with portions in cross section, of a modification of the embodiment shown in Fig. 3C in which the outer conductor is shaped to reduce the velocity of propagation;

Fig. 6 is an end view of another form of coaxial cable which is utilized in other forms of antennas in accordance with the invention, the outer conductor comprising a multiplicity of metal laminations separated by insulating material and the inner conductor being of a conventional form, the outer and inner conductors being separated by dielectric material;

Fig. 7A is an end view of still another form of coaxial cable which can be utilized in antennas in accordance with the invention, in which both inner and outer conductors are laminated and are separated by dielectric material;

Fig. 7B is a longitudinal view, with portions in cross section, of a section of cable of the type shown in Fig. 7A;

Fig. 8 is a graphical representation showing the attenuation as a function of frequency (A) of a cable of the type shown in Fig. 7A and (B) of a standard coaxial cable of the same outer dimensions;

Fig. 9 is a cross-sectional longitudinal view of an antenna system in accordance with the invention utilizing a laminated center conductor as shown in Figs. 3A and 3C;

Fig. 10 is a cross-sectional longitudinal view of a modification of the antenna of Fig. 9;

Fig. 11 is a perspective view of a modification of the arrangement of Fig. 2A in which a multiplicity of filamentary rods of irregular size, shape and disposition replaces the laminated structure;

Fig. 12 is an end view of a two-conductor line forming part of an antenna system in accordance with the invention, each of the conductors comprising a multiplicity of tiny filaments separated by insulating material and the two conductors being separated by a dielectric;

Fig. 13 is a longitudinal view, with portions in cross section, of another antenna system in accordance with the invention utilizing a cable of the type shown in Fig. 11;

Fig. 14 is an end view of another form of coaxial cable which can be used in antennas in accordance with the invention, in which all of the space between an outer sheath and an inner core is filled with metal laminations insulated from one another;

Fig. 15 is a graphical representation showing the approximate variation of current density with radial distance in the structure of Fig. 14; and

Fig. 16 is a cross-sectional longitudinal view of an antenna system in accordance with the invention utilizing a laminated structure of the type shown in Fig. 14.

Referring more particularly to the drawings, consider an electromagnetic wave propagating through space in the neighborhood of, and parallel to the surface of an electrical conductor such as copper, silver or aluminum, for example. This situation is shown diagrammatically in connection with the conductor 10 in Fig. 1A which can be representative of many phenomena. It can illustrate, for instance, the transmission of an electromagnetic wave through a coaxial line, or along an open or shielded two-wire system, or a wave propagating through a metal wave guide. It can also represent the situation in the vicinity of a transmitting or receiving antenna. Clearly a very broad class of electrical phenomena involving the transfer or periodic oscillation of electromagnetic energy in the vicinity of electrical conductors is represented in Fig. 1A.

The wave propagating in Fig. 1A is necessarily accompanied by electric currents flowing in the metal. Because of these currents, power is removed from the electromagnetic field and dissipated in the metal. This effect is nearly always undesirable. The distribution of this current in a direction away from the surface is shown in Fig. 1B where it has been assumed that the conductor is thick compared to δ , if the frequency is sufficiently high. Because of the well-known "skin effect," most of the current flows in a thin layer near the surface. The distance from the surface at which the current density has fallen to $1/e = 0.3679 \dots$ times its value at the surface is known (as mentioned above) as the "skin depth" and is denoted by δ . The distance is expressed in terms of the frequency (F) under consideration and the permeability (μ) and conductivity (σ) of the metal in Equation 1 above. With a given amplitude of the electromagnetic wave, the amount of power lost to the metal will be proportional to $1/\delta\sigma$. Referring to Equation 1, it can be seen that the power loss is proportional to $1/\sqrt{\sigma}$ so that normally the power loss is minimized by choosing a metal of high conductivity, such as copper or silver.

Suppose that it were possible to arbitrarily increase without greatly changing σ . It is clear that in such a situation the power loss from the electromagnetic wave would be greatly decreased. It has been discovered that it is possible to do just this thing, and the present invention is based on this discovery. A simple embodiment will be considered first and then more general cases will be discussed. Referring to Fig. 2A, there is again shown an electromagnetic wave propagating near the surface of an electrical conductor 20. The relationship of the electric and magnetic vectors and of the direction of propagation of the electromagnetic wave are shown. The conductor in Fig. 2A is no longer a solid piece of metal but is composed of many spaced laminae 21 of metal of thickness W arranged parallel to the direction of propagation and parallel to the magnetic vector as shown. These laminae are very thin compared to δ and are separated by empty space or any appropriate dielectric 22 such as air, polyethylene, polystyrene, quartz, or polyfoam, for example, the thickness thereof being represented by t . Whatever the dielectric is, suppose that its dielectric constant is ϵ_r , and suppose that the conductivity of the metal is σ , as before. Fig. 2A is representative of many situations of which a few will be indicated later. The particular cases being considered in which the magnetic vector is parallel to the surface of the com-

posite conductor are not representative of all cases, as will be indicated below.

Since the stack of metal laminae in Fig. 2A will not conduct direct current in a direction perpendicular to the plane of the laminae, it is possible by conventional means to measure an average dielectric constant associated with this direction. This average dielectric constant will be denoted by $\bar{\epsilon}$ or ϵ_t and is given by the expression

$$\bar{\epsilon} = \epsilon_2(1 + W/t) \text{ farads per meter} \quad (3)$$

An electromagnetic wave propagates in a material of dielectric constant ϵ and permeability μ_0 with a velocity $1/\sqrt{\epsilon\mu_0}$. Let it now be assumed that it has been arranged that the electromagnetic wave in Fig. 2A is traveling with the velocity an electromagnetic wave will have in a medium of dielectric constant $\bar{\epsilon}$ and permeability μ_0 . This condition can be arranged by properly disposing suitable dielectric material in all or part of the region traversed by the wave outside the stack. The condition can also be fulfilled by properly shaping adjacent electrical conductors, and a particularly advantageous way of bringing about this condition will be described later in connection with Fig. 5.

Under the conditions mentioned, if W is small compared to δ , we can define an effective skin depth δ_e by

$$\delta_e = (W + t)\sqrt{3}\left(\frac{\delta}{W}\right)^2 \text{ meters} \quad (4)$$

If the stack of laminations is several times δ_e in thickness, the current density will decrease exponentially into the stack and be reduced by one neper at a distance below the surface equal to δ_e . This "increased" or "effective" skin depth is shown in Fig. 2B. Furthermore, the effective conductivity σ_e of the stack of laminations in the direction of propagation of the wave is given by

$$\sigma_e = \frac{1}{1 + t/W} \quad (5)$$

We can now form the term

$$\frac{1}{\delta_e \sigma_e}$$

and find that it is given by

$$\frac{1}{\delta_e \sigma_e} = \frac{1}{\sigma \delta} \frac{1}{\sqrt{3}} \left(\frac{W}{\delta} \right) \quad (6)$$

It is immediately observed that the power lost from the electromagnetic wave has been reduced by a factor

$$\frac{1}{\sqrt{3}} \left(\frac{W}{\delta} \right)$$

For instance, if the laminae in a typical case are $1/10$ skin depth thick, the power taken from the wave will be only $1/17$ of the power that would be lost to a solid conductor.

The increased skin depth described above not only is effective in greatly reducing conductor losses, but has a further major concomitant advantage. Referring to Equation 1 it can be seen that conductor losses generally increase as the square root of the frequency. This variation with frequency very often is equally as troublesome as the losses themselves. A simple but extremely wasteful way to reduce this effect is to make the metal conductor very thin. Suppose for instance that the skin depth is δ at the highest frequency under consideration. If the conductor is no thicker than δ the losses will clearly remain uniform, but high, from very low frequencies up to this maximum. Similarly, with the arrangement of Fig. 2A the size of the stack can be limited to the thickness δ_e determined by Equation 4 at the highest frequency, and thereby obtain uniform loss. But since δ_e may be made as large as desired by making W small enough, this uniform loss can be achieved without accepting greatly increased losses at the lower frequencies.

The general situation indicated in Fig. 2A can have

many specific embodiments and variations of which a few will now be described.

In Figs. 3A and 3C there is shown, in end view and longitudinal view, respectively, with portions in cross section, a coaxial transmission line 30 constructed in a conventional way except that the inner conductor 31 is formed of many thin coaxial laminations of metal 32 and of some suitable dielectric 33. The region between the inner and outer conductors 31 and 34 is filled with insulating material 35 of dielectric constant equal to the average dielectric constant of the stack as described above and in Equation 3. Fig. 3B shows the approximate distribution of current in the inner and outer conductors 31 and 34. The current is observed to decrease rapidly with distance into the solid outer conductor 34 and much more slowly into the laminated inner conductor 31. Because the current falls off more slowly with distance into the inner conductor than it would if the inner conductor were solid, the attenuation of the transmission line is much less than it would be with the conventional solid inner conductor which usually has a larger resistance than the outer conductor. The line in Fig. 3A is shown with an inner core 36. This core in specific instances can be metal or dielectric or even be omitted altogether. The dielectric material 35 shown might equally well fill only part of the region between inner and outer conductors (as shown in Fig. 3D wherein the dielectric 37 takes up only a portion of the space between the inner and outer conductors) and would have in that case a larger value than that described in Equation 3. The dielectric 37 may be held in place by spacers 38, if desired, and may be in the form of one or more dielectric cylinders surrounding the inner conductor.

By way of example, the behavior of a specific line of the type described above is shown in Fig. 4. The line has a core of insulating material 0.146 inch in diameter. On this core are laminated 50 layers of insulation each 0.976×10^{-3} inch thick and 50 layers of copper each 0.197×10^{-3} inch thick. The over-all diameter of the inner conductor is 0.264 inch and the inner and outer diameters of the outer conductor are, respectively, 4.000 and 4.166 inches. Fig. 4 compares the attenuation of a selected length (94 1/8 inches) of this line (curve A) with that of a conventional line (curve B) having a solid inner conductor of the same diameter, as the dielectric constant of the insulating material between the inner and outer conductors is varied. The attenuation of the new line is seen to reach a minimum for $\epsilon = \bar{\epsilon}$, where $\bar{\epsilon}$ has the value given in Equation 3, and this minimum value is much less than that of the conventional line. Even for values of ϵ appreciably different than $\bar{\epsilon}$ (as shown in Fig. 4), the new line has advantages over the conventional one.

Fig. 5 is a longitudinal view of a transmission line 40 somewhat similar to that shown in Fig. 3A. This example indicates how the velocity of the wave in the line can be adjusted to the proper value by appropriately shaping the outer conductor 41 (in a manner well known) to reduce the velocity of propagation. This arrangement is equally as effective as that shown in Fig. 3A in achieving reduced transmission losses. The inner conductor 42 is similar to the inner conductor 31 of the arrangement of Fig. 3A. The core 46 is similar to the core 36.

In Fig. 6 is shown another possible embodiment 50 of the invention in which a stack of insulated metal laminations makes up the outer conductor 51. The inner conductor 52 can be a solid or tubular conductor and it is separated by a dielectric 53 from the laminated outer conductor 51 comprising alternately disposed metal and insulating layers 55 and 56, respectively. A sheath 54 of metal or other appropriate material or combination of materials, surrounds the outer conductor 51 for shielding purposes.

In Figs. 7A and 7B still another arrangement is illustrated, comprising a laminated inner conductor 61 of alternately disposed laminations of metal and insulating

material 66 and 67, respectively, separated by a main dielectric 63 from an outer conductor 62 which is formed of similar laminations 68 and 69, respectively. A sheath 65 surrounds the outer conductor. The dielectric constant of the main dielectric 63 is made equal to $\epsilon_2(1+W/t)$ where ϵ_2 is the dielectric constant of the laminations 67 and 69, W is the average thickness of a metal lamination 66 or 68, and t is the thickness of an average lamination 67 or 69 of insulation. By choosing proper values of ϵ_2 , W and t , the average dielectric constant $\bar{\epsilon}$ of each stack (61 and 62) can be made equal to one another although the ϵ_2 , W and t of one stack may be different from that of the other.

Again by way of example, the behavior of a specific line of the type shown in Fig. 7A is shown in Fig. 8. This line has a dielectric core 64 of diameter .066 inch and carries a stack 61 of 50 layers of copper 66 and 50 layers of insulation 67 each .0001 inch thick. The outer conductor 62 has an inner diameter of 0.330 inch and also carries a stack of 50 laminations each of metal and insulation similar to that of the inner conductor. The dielectric constant of the material 63 between inner and outer conductors is adjusted to the optimum value given in Equation 4. Fig. 8 shows the attenuation (curve A) of this cable 60 as a function of frequency from 0 to 50 megacycles per second. Also shown is the attenuation curve (curve B) for a conventional, airfilled coaxial line of nearly the same dimensions (diameter of inner conductor 0.1000 inch and inside diameter of outer conductor 0.375 inch). The decreased attenuation and less rapid variation with frequency are clearly demonstrated.

With the cables shown in Figs. 3A, 6 and 7A there exists an optimum proportioning of the thickness of the metal and dielectric lamina. For best results, each dielectric lamina is made one-half the thickness of a metal lamina, or, in some specific instances, greater than half this thickness.

Fig. 9 is a longitudinal cross-sectional view of an antenna structure embodying, or which is adapted to be connected to, a composite conductor or cable of the type shown in Fig. 3C. In the antenna of Fig. 9, the shield 34 is terminated in the form of a flat circular plate 34A having a central aperture therein and extending but a distance approximately corresponding to a quarter wavelength in the dielectric of the frequency to be radiated. The central composite conductor 36A comprising a core 36 (which may be omitted) and a stack 31 of alternately disposed layers of metal 32 and insulation 33 is continued on past the plate 34A through the central opening therein for a distance approximately a quarter of a wavelength in the dielectric of the frequency to be propagated from the antenna. Surrounding this central extended portion 36B of the conductor 30 is a mass 35A of the same material as the main dielectric member 35 of the cable 30. The mass 35A may have its end rounded off as shown in the drawing. The radiation pattern from the antenna of Fig. 9 is similar to that of corresponding antenna systems employing solid conductors. The structure of Fig. 9, however, has the advantage that the power loss in the antenna structure itself is reduced because of the reduction of skin effect losses and also has the further advantage that it can be readily coupled to antenna lead-ins of the laminated type which also have a greatly reduced attenuation of skin effect losses.

The structure shown in Fig. 10 is similar to the arrangement of Fig. 9 except that instead of the sheath 34 terminating in a circular flat plate 34A it is instead terminated in a circular skirt 34B of a length approximately one-quarter wavelength in the dielectric of the frequency to be radiated. As in Fig. 9, the central portion 36B of the composite conductor extends past the beginning of the skirt by approximately one-quarter wavelength in the dielectric of this frequency. Except for these differences the structure of Fig. 10 is like that of Fig. 9. The radi-

ation pattern from the structure 10 is different from that of Fig. 9 and corresponds to the radiation pattern of a folded dipole antenna constructed in substantially the same way except that solid elements are used. The advantages of the arrangement of Fig. 10 are similar to those of the antenna of Fig. 9.

In Fig. 2A there is shown drawn in perspective a laminated conductor 20 made up of alternately disposed metal layers 21 and insulating layers 22. It is clear that a similarly effective arrangement of conductors would be that in which each metal lamination is divided into a series of rectangular rods spaced by insulation. It is now also clear that the rods need not be regularly arranged and indeed need not be even rectangular in section. The conductor could in fact be composed as shown in Fig. 11 of an irregularly arranged group 90B of conductors 95 of irregular cross section spaced from one another by some suitable solid dielectric 96 or air or vacuum. In fact, all that is required in order that the conductor 90B in Fig. 11 be as effective as the laminations 21 in Fig. 2A for reducing conductor losses is that each of the individual filamentary 95 conductors have a maximum dimension in the direction of the electric vector small compared to δ . Under those circumstances a bundle of filamentary conductors as Fig. 11 may replace the laminations in the examples given in Figs. 3A, 5, 6 and 7A.

Suppose now the further step is taken of requiring the filamentary conductors 95 to have the largest dimension in any direction perpendicular to their length small compared to δ . It is now no longer required that the magnetic vector be parallel to the surface of the composite conductor. Under these circumstances other specific embodiments of the invention can be considered.

For example, in Figure 12 there is shown a two-conductor transmission line 100 of a type in common use with each of the conductors 101 and 102 constructed as shown in Fig. 11. Substantial improvement in performance over the conventional two-wire system can be expected. Suitable dielectric 103 is shown joining the two composite conductors 101 and 102 so that the electromagnetic wave will propagate along the system with a velocity appropriate to the average transverse dielectric constant of the bundles.

Fig. 13 shows a simple dipole antenna 140 which is illustrative of much more complicated antenna systems. The antenna is provided with composite conductors 141 and 142 of the filamentary type shown in the last two figures and these conductors are encased in appropriate dielectric material 143 chosen to provide the proper velocity of wave propagation. The conductors 141 and 142 are fed to the antenna through a conductor of the type shown in Fig. 12, that is, the two composite conductors 141 and 142 when outside the dielectric 143 are separated by a dielectric member 144 (similar to the central dielectric member 103 in Fig. 12). The ends 145 and 146 of the composite conductors 141 and 142 are then conducted to any desired transmitting apparatus. It is to be understood that the dielectric member 144 between the conductor 141 and 142 may be as long as required (the length being determined by the length of the lead-in for the antenna). The radiation pattern of the structure of Fig. 13 is similar to that of dipoles employing solid elements but the loss is less and ready coupling to a lead-in of the type of Fig. 12 is afforded.

In all the examples of the invention so far considered, special means have been provided to assure that the velocity of propagation of the electromagnetic wave along the system is appropriate to the average transverse dielectric constant of the composite conductors. It has been pointed out that under these conditions the currents penetrate deeply within the composite conductor. It is of course then that the electromagnetic wave itself penetrates equally deeply into the conductor. Within the conductor the wave has, as might be expected, an intrinsic velocity of propagation just appropriate to the average transverse

dielectric constant. Thus, if the region within which the electromagnetic wave propagates is completely filled with the composite conductor, the condition on the velocities is automatically fulfilled. Fig. 14 illustrates a coaxial transmission line 150 constructed in accordance with this principle. The entire region between the sheath 151 and the core 152 (which may be either of solid tubular metal, either magnetic or non-magnetic, or of dielectric material), is filled with alternate laminae of thin metal and dielectric cylinders 153 and 154, respectively. The metal laminae are, as in the embodiments described above using laminated structures, made as thin as possible compared with the skin depth δ . The dielectric laminations are also made very thin compared to δ and, as pointed out above, in many cases it is preferable to make them smaller than the metal laminations. The material of which the dielectric laminations are made is not critical but is best chosen to have high insulating power and low dielectric constant.

In Fig. 15, an approximate curve of current density within the transmission line 150 vs. radial distance is shown. It will be observed that in the outer layers, current flows in one direction, and that in the inner layers it flows in the opposite direction. The attenuation of such a transmission line 150 is much less than the attenuation of a conventional line of equal outside dimensions.

Fig. 16 shows an antenna structure which is somewhat similar to that of Fig. 10 except that it embodies, or is coupled to, a composite cable of the type shown in Fig. 14. In the arrangement of Fig. 16, the inner half of the stack 150A comprising the metal laminations 153 and insulating layers 154, extends out, by substantially one-quarter of a wavelength in the dielectric of the frequency to be radiated past the point where the outer portion of the stack 150B is shaped to form a circular skirt 150C surrounding the stack 150 and extending back, as shown in the drawing, a distance substantially one-quarter wavelength in the dielectric of the frequency. Surrounding the members 150A, B, C and D is a mass 155, which may be rounded at the end, of dielectric material having a dielectric constant which matches the average dielectric constant of the composite conductor 150. The radiation pattern of the antenna of Fig. 16 is quite similar to that of the structure of Fig. 10. The advantages of low skin effect loss in the antenna structure and ready coupling to a composite conductor of the laminated type are similar to those of Figs. 9 and 10.

The manner in which the various antenna structures described above can be coupled to coaxial cables and other lead-in members is described in the parent application in which is also described ways of making composite conductors forming parts of the antenna structures disclosed herein. It is obvious that many changes can be made in the embodiments described above. The various embodiments and the modifications thereof described herein are meant to be exemplary only and they do not by any means comprise a complete list of conductors to which the present invention is applicable and it is obvious that many more will occur to those skilled in the art. It is intended to cover all such obvious modifications as clearly fall within the scope of the invention.

What is claimed is:

1. An antenna comprising first and second conducting members, at least one of said members being a composite conductor comprising a plurality of elongated conducting portions spaced by means including insulating material, each of said conducting portions having at least one dimension in a direction substantially transverse to the direction of wave propagation along the length thereof which is small compared with its appropriate skin depth at the frequency of electromagnetic wave to be radiated therefrom, said composite conductor extending in a direction away from the antenna end of the other conductor and defining a radiation element of said antenna, said composite conductor being embedded beyond the end of said other conductor in dielectric material having a dielectric constant of a value to produce a velocity of propa-

gation therein which matches that of the wave in said composite conductor.

2. The combination of elements as claimed in claim 1 wherein said elongated conducting portions are laminations.

3. The combination of elements as in claim 1 in which said elongated conducting portions are of filamentary material.

4. The combination of elements as in claim 1 in which said elongated conducting portions are in the form of thin cylinders positioned within and coaxial with said other conducting member, said other conducting member being a solid metal cylinder which terminates in a solid circular plate.

5. The combination of elements as in claim 1 in which said elongated conducting portions are in the form of thin cylinders positioned within and coaxial with said other conducting member, said other conducting member being a solid metal cylinder which terminates in a circular skirt.

6. The combination of elements as in claim 1 in which said elongated conducting portions are in the form of thin cylinders positioned within and coaxial with said other conducting member, said other conducting member being a solid metal cylinder which terminates in a circular skirt of a length substantially one-quarter wavelength in the insulating material of the frequency to be radiated.

7. The combination of elements as in claim 1 in which said elongated conducting portions are in the form of thin cylinders positioned within and coaxial with said other conducting member, said other conducting member being a solid metal cylinder which terminates in a circular skirt of a length substantially one-quarter wavelength in the insulating material of the frequency to be radiated, the thin cylinders extending beyond the beginning of the skirt for a distance substantially one-quarter of a wavelength in the insulating material of this frequency.

8. An antenna comprising as a radiation element thereof a multiplicity of elongated conducting portions spaced by means including insulating material, each of said conducting portions having at least one dimension in a direction substantially transverse to the direction of wave propagation down the length thereof which is small compared with its appropriate skin depth at the frequency of electromagnetic wave to be radiated therefrom, said elongated conducting portions being in the form of thin cylinders positioned within and coaxial with an outer solid metal cylinder which terminates in a solid circular plate, the thin cylinders extending beyond the surface of the plate for a distance substantially one-quarter of a wavelength in the insulating material of the frequency to be radiated.

9. An antenna comprising as a radiation element thereof a first conductor, a second conductor, and a third conductor which is at least as thin as the skin depth of penetration of waves at the frequency of operation of said antenna and which is spaced parallel from said first and second conductors by first and second dielectric materials respectively said first and third conductors extending in a direction away from the end of said second conductor, said first and third conductors being imbedded beyond the end of said second conductor in a dielectric material having a dielectric constant of a value to produce a velocity of propagation therein which substantially matches that of the wave traveling in said first and third conductors.

10. The combination of elements as in claim 1 in which said elongated conducting portions are in the form of thin cylinders positioned within and coaxial with said other conducting member, said other conducting member being a solid metal cylinder which terminates in a solid circular plate, the thin cylinders extending beyond the surface of the plate for a distance substantially one-quarter of a wavelength in the insulating material of the frequency to be radiated.

11. The combination of elements as in claim 1 in

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which said first and second conducting members each comprise a plurality of elongated conducting portions spaced by means including insulating material and said conducting portions are arranged in two groups of parallel positioned portions in the shape of a dipole.

12. The combination of elements as in claim 1 in which said first and second conducting members each comprise a plurality of elongated conducting portions spaced by means including insulating material and said conducting portions are arranged in two groups of parallel positioned portions in the shape of a dipole with ends pointing in opposite directions.

13. The combination of elements as in claim 1 in which said first and second conducting members each comprise a plurality of elongated conducting portions spaced by means including insulating material and said conducting portions are in the form of thin coaxially arranged cylinders forming one of said conducting members and, the inner half of said cylinders extending beyond the outer half of said cylinders by a distance correspond-

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ing to substantially one-quarter wavelength in the insulating material of the frequency to be radiated by the antenna, the outer half of the cylinders terminating in a skirt surrounding all the cylinders, the skirt and the extension cylinders being surrounded by dielectric material.

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