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2,825,761

MAGNETICALLY LOADED ELECTRICAL CONDUCTORS

Filed June 29, 1951

2 Sheets-Sheet 1

FIG. 1

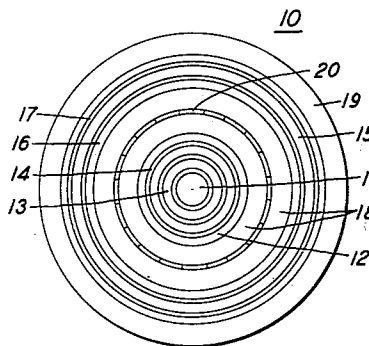


FIG. 2

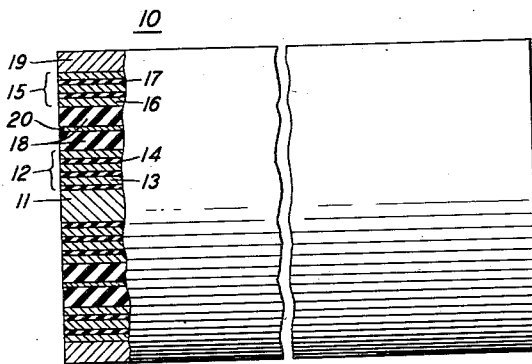


FIG. 3

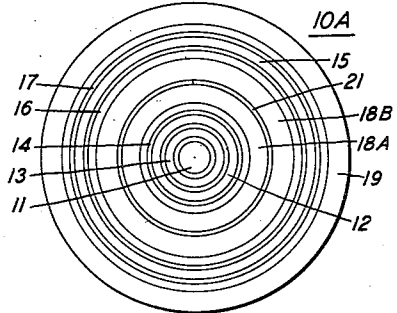


FIG. 4

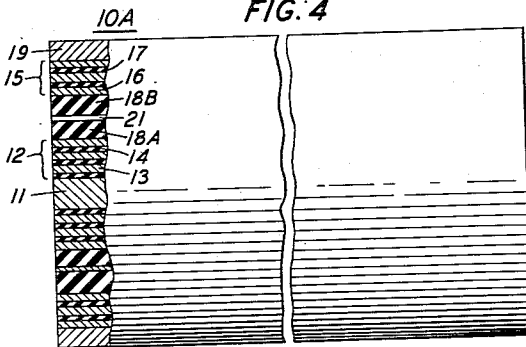


FIG. 5

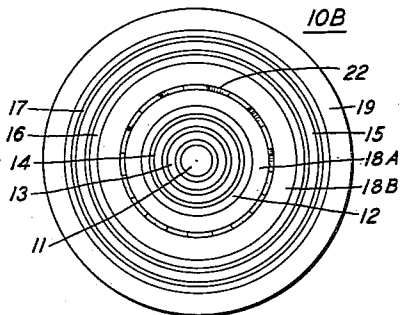
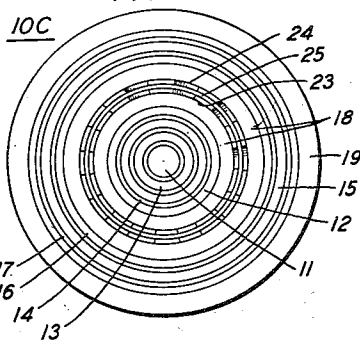


FIG. 5A



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FIG. 6

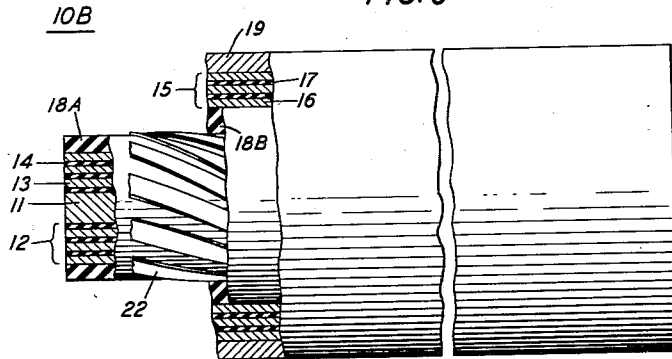


FIG. 7

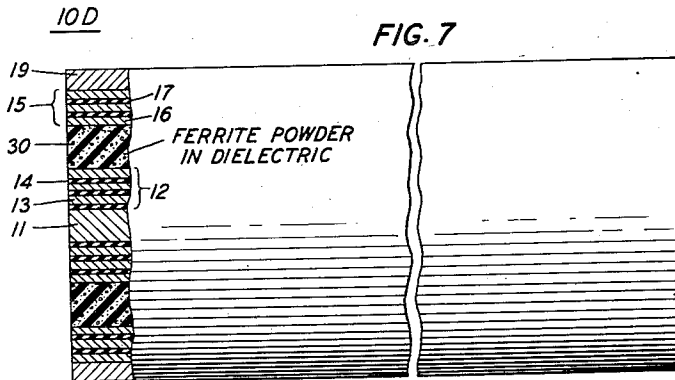
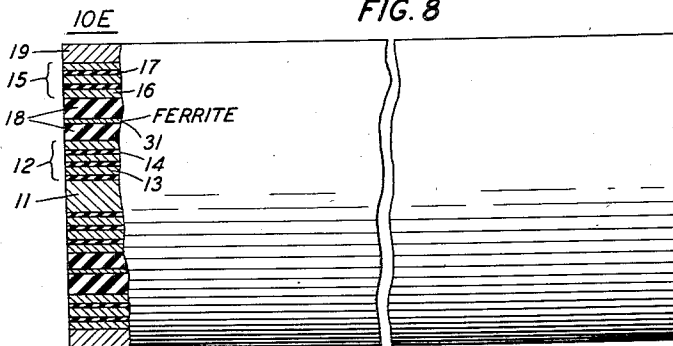


FIG. 8



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MAGNETICALLY LOADED ELECTRICAL CONDUCTORS

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Application June 29, 1951, Serial No. 234,358

12 Claims. (Cl. 178-45)

This invention relates to electrical conductors and more particularly to composite conductors formed of a multiplicity of insulated conducting portions.

It is an object of this invention to improve the current distribution in conductors of the type comprising a large number of insulated conducting portions, and particularly to effect such improvement by magnetic loading.

In the copending application of A. M. Clogston, Serial No. 214,393, filed March 7, 1951, and which issued on October 30, 1956, as Patent 2,769,148, there are disclosed a number of composite conductors, each of which comprises a multiplicity of insulated conducting elements of such number, dimensions, and disposition relative to each other and to the orientation of the electromagnetic wave being propagated therein as to achieve a more favorable distribution of current and field within the conducting material. In one specific embodiment disclosed in Figs. 7A and 7B of the Clogston application, two coaxially arranged composite conductors are separated by a dielectric material, each of the composite conductors comprising a multiplicity of thin metal laminations insulated from one another by layers of insulating material, the smallest dimensions of the laminations being in the direction perpendicular to both the direction of wave propagation and the magnetic vector. Each metal lamination is many times (for example, 10, 100, or even 1000 times) smaller than the factor δ , which is called one skin thickness or one skin depth. The distance δ is given by the expression

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

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 in mhos per meter. The factor δ measures the distance in which the current and field penetrating into a slab of the material many times δ in thickness will decrease by one neper; i. e., their amplitude will become equal to

$$\frac{1}{e} = 0.3679 \dots$$

times their amplitude at the surface of the slab.

It was pointed out in the Clogston application that when a 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, resulting in a more uniform current distribution in the laminated conductor and consequently lower losses. The critical velocity for the type of structure just described is determined by the thickness of the metal and insulating laminae and the dielectric constant of the insulation between the laminae in the composite conductors. The critical velocity can be maintained by making the dielectric constant of the main dielectric,

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that is, the dielectric material between the two composite conductors, equal to

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

where ϵ_1 is the dielectric constant of the main dielectric element between the two composite 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 lamina in meters. The insulating laminae are also made very thin, and an optimum thickness for certain structures of this general type is that in which each insulating lamina is one-half of the thickness of a metal lamina.

The present invention relates to improvements in composite structures of the type just described and also in other related structures, such as, for example, others described in the above-mentioned Clogston application.

When the wave velocity of propagation is controlled in one of these structures by the use of dielectric material, the current density in the conductors for a given power level is thereby increased; and the conductor losses are greater than they would be if this increase in current density had not been necessary.

In accordance with the present invention, the wave velocity in structures of the general type mentioned above can be controlled in such a way that an increased current density does not result. For example, a properly shaped conductor in accordance with the invention produces a decrease in current density. In Fig. 5 of the above-mentioned Clogston application, there is shown a conductor which by proper shaping can produce a decrease in current density, but this type of structure presents a wave velocity that varies with frequency and thus limits the usefulness of the device.

In the various structures of the present invention, magnetic material is used in a number of composite conductors to produce the required velocity of wave propagation, making possible the use of dielectric materials with lower dielectric constants than those of the corresponding members described in the above-identified Clogston application. The advantage of each of these arrangements is that it reduces the current density in the composite conductor and, therefore, tends to decrease the losses.

In one specific illustrative embodiment of the present invention, a composite conductor of the type in which two laminated concentric conductors are separated by a main dielectric member has one or more magnetic tapes or cylinders buried in the central dielectric member which has a relative dielectric constant as near unity as possible. In another embodiment, a magnetic ferrite is used with the main dielectric member, the ferrite being introduced in the form of small particles buried in the dielectric member. In still another embodiment, cylinders of a magnetic ferrite are embedded in the central dielectric member. Various modifications of these typical embodiments also constitute a part of the present invention.

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. 1 is an end view of a coaxial composite conductor in accordance with the invention, the outer conductor comprising a multiplicity of metal laminations separated by insulating material and the inner conductor being similar in this respect to the outer conductor, the space between these two conductors being filled with a dielectric member having a plurality of magnetic tapes arranged longitudinally therein;

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Fig. 2 is a longitudinal view, with portions broken away, of the composite conductor of Fig. 1;

Fig. 3 is an end view of a modification of the arrangement of Fig. 1, the tapes of the arrangement of Fig. 1 being replaced by a single tape wrapped in the form of a cylinder;

Fig. 4 is a longitudinal view, with portions broken away, of the arrangement of Fig. 3;

Fig. 5 is an end view of a modification of the arrangement of Fig. 1 in which one or more tapes are wrapped spirally within the main dielectric member;

Fig. 5A is an end view of a modification of the arrangement of Fig. 5 in which the spiralled tapes are arranged in a plurality of layers;

Fig. 6 is a longitudinal view, with portions broken away, of the composite conductor of Fig. 5;

Fig. 7 is a longitudinal view of another embodiment of the invention, in which a magnetic ferrite is used in powdered form in the main dielectric member; and

Fig. 8 is a longitudinal view of a modification of the arrangement of Fig. 7 in which a cylinder of a ferrite is embedded in the main dielectric member.

Referring more particularly to the drawings, Figs. 1 and 2 show, by way of example, a conductor 10 in accordance with the invention, Fig. 1 being an end view and Fig. 2 being a longitudinal view. The conductor 10 comprises a central core 11 (which may be either of metal or dielectric material), an inner conductor or stack 12 formed of many laminations of metal 13 spaced by insulating material 14, an outer conductor or stack 15 formed of a multiplicity of layers of metal 16 spaced by insulating material 17 and separated from the inner conductor 12 by a dielectric member 18, and an outer sheath 19 of metal or other suitable shielding material. As disclosed in the above-mentioned Clogston application, each of the metal layers 13 and 16 is very thin compared to the skin depth of the conductor being used, which, for example, can be copper, silver, or aluminum. The insulating layers 14 and 17 are also made very thin and may be of any suitable material. Examples of satisfactory materials are: air, polyethylene, polystyrene, quartz, or polyfoam. Preferably, the insulating layers are of the order of one half the thickness of each metal layer, although this is not necessarily true in all cases. The inner conductor 12 has 10 or 100 or more metal layers 13, and the outer conductor 15 has a somewhat similar number of metallic layers 16, though there need not be exactly the same number as in the inner conductor 12. Since there are a large number of insulating and metallic layers, it makes no difference whether the first or the last layer in each stack (12 or 15) is of metal or of insulation.

In accordance with the present invention, the dielectric member 18 has embedded therein one or more magnetic members 20 in the form of longitudinal tapes. The tapes can be laid in the dielectric member 18 during the extrusion thereof if the dielectric member is, for example, of a foamed plastic with as high a percentage of foaming as is consistent with necessary mechanical properties. The loss in a composite conductor of the type shown in Figs. 1 and 2 and using the more common types of insulation between the metallic laminae (compared with the same conductor without the magnetic member 20) is less, by a factor from about 6 to 15.

In order to realize the advantages of the arrangement just described, it is necessary that the magnetic tape member 20 (or other magnetic means to be described below in connection with the other embodiments and modifications) be such as to not increase the dissipation in the space between the composite conductors 12 and 15 appreciably, or, in other words, the permeability and resistivity should be as high as possible. This is especially true since the losses which would occur have a frequency characteristic and hence tend to degrade the

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desirable flat characteristic obtained from a cable of the type shown in Fig. 1 without the magnetic member 20.

In order to appreciate how magnetic loading, that is, the introduction of magnetic material, improves the conductor 10 and also the conductors to be described later in connection with Figs. 3 to 8, inclusive, reference will be made to a more generalized statement of Equation 2 in which the metallic laminae and the insulation between them have a permeability μ_2 while the main dielectric element 18 has a permeability μ_1 . Under these conditions Equation 2 becomes:

$$\bar{\mu}_1 \bar{\epsilon}_1 = \mu_2 \epsilon_2 \left(1 + \frac{W}{t} \right) \quad (3)$$

where $\bar{\mu}_1$ is the average permeability of the main dielectric element 18 in henries per meter, $\bar{\epsilon}_1$ is the average dielectric constant of the same member in farads per meter, μ_2 is the permeability of both the metal and insulating material used in the laminae (assumed to be the same) in henries per meter and the other elements are the same as in Equation 2. Examining Equation 3 and appreciating that the right-hand portion of the equation is a constant, one sees that increasing $\bar{\mu}_1$ will make possible a corresponding decrease in $\bar{\epsilon}_1$. A desirable material for the central dielectric member 18 is one which has a relative dielectric constant as near 1.0 as possible. Such a material can be air or an appropriate polyfoam, for example, and under these conditions, $\bar{\mu}_1$ is given the value of

$$\mu_2 \epsilon_2 \left(1 + \frac{W}{t} \right)$$

As certain structures of this general type have an optimum value of

$$\frac{W}{t}$$

which is 2, $\bar{\mu}_1$ can be made equal to $3\mu_2 \epsilon_2$, or, stated differently, the relative value of $\bar{\mu}_1$ can be three times the relative dielectric constant ϵ_2 as the relative value of μ_2 is preferably made as near 1.0 as possible. Since no material exists having negligible conductivity, a relative dielectric constant of 1.0 and a relative permeability appreciably different from 1.0, the central member between the stacks 12 and 15 cannot be of homogeneous material. This difficulty can be resolved by the use of composite materials. For example, in Figs. 1 and 2, a composite material consists primarily of the low dielectric constant insulating material 18 filling most of the space together with ferromagnetic tapes 20 having relative permeabilities of 100 or more and occupying a fraction of the total space approximately equal to $\bar{\mu}_1/\mu$, where μ is the permeability of the material used. Since the power propagated through the system is proportional to the square of the total magnetic flux which in turn is proportional to the permeability times the current density (the factors of proportionality being geometric in nature), then an increase in the permeability will decrease the current density required to propagate a given power providing the geometrical factors are not changed.

In the arrangement of Fig. 3, the longitudinal tape 20 is replaced by a single tape 21 whose width equals the circumference of the structure at the point of insertion. The tape 21 is wrapped with a longitudinal seam around the first section 18A of the main dielectric 18, thus serving to divide sections 18A and 18B from one another. Except for this difference, the conductor 10A of Figs. 3 and 4 is exactly like the conductor 10 of Figs. 1 and 2 and the description given above for Figs. 1 and 2 applies to this arrangement also.

In the arrangement of Figs. 5 and 6, the conductor 10B has one or more tapes 22 wrapped spirally around the first section 18A of the main dielectric 18. Except for these differences, the conductor 10B is similar to the conductor 10 of Figs. 1 and 2.

When the permissible thickness of the tapes 22 of Figs.

5 and 6, as determined by the top frequency to be propagated, is very small, it may be necessary or favorable to have several layers of tapes 23, 24, etc., insulated from each other by one or more insulating layers 25, which may be if desired of the same material as the central dielectric member 18. Fig. 5A shows a conductor 10C of this type. In the conductor 10C, it is desirable to proportion the thickness and dielectric constants of the tapes 23, 24, etc. to satisfy the relations shown in Equation 2 above. In any case, the sum of the thickness of the tapes 23 and 24 is determined so as to increase the total flux by the desired amount.

It is desirable to place the tapes 23 and 24 and also the members 20, 21, and 22 in a neutral plane, that is, in a region where E_z (the longitudinal component of the electric field) is zero so as to minimize the dissipation due to current flow. At the same time the individual tapes must be kept thin both to minimize the dissipation due to eddy currents and to minimize the change in effective permeability due to the shielding effect of eddy currents. Both of these reasons require that the thickness be small compared to the depth of penetration in the metal.

Two additional arrangements, each using magnetic ferrites, are shown in Figs. 7 and 8, respectively. Ferrites and their properties are described in an article entitled "Ferrites: New magnetic materials for communication engineering," by V. E. Legg in the May 1951 number of Bell Laboratories Record at page 203. In the structure of Fig. 7, a composite conductor 10D is illustrated which is like that of Figs. 1 and 2 except that the dielectric member 18 and its accompanying magnetic member 20 are replaced by a plastic dielectric member 30 formed, for example, by mixing the magnetic ferrite in the form of a finely divided powder with a plastic dielectric material such as polyethylene foam. In the conductor 10E of Fig. 8, the ferrite is in the form of a cylinder 31 whose permeability and dimensions are appropriate to give the desired increase in magnetic flux in the dielectric 18. In the arrangement of Fig. 8, the placing of the cylinder 31 in the region of low longitudinal electric field is not as critical as in the case when one or more of the metal members 20, 21, 22, 23, and 24 are used, because the intrinsic admittance of the material 31 is much lower and little current flows in any case. However, the dielectric constant of the material must be taken into account in either of the arrangements of Figs. 7 and 8. Because of the relatively large dissipation factor of the ferrites, care must be taken to keep the total volume of ferrite at a minimum.

It is obvious that the invention is not restricted to the specific forms of composite conductors shown, as the invention is obviously applicable to many of the other arrangements disclosed in the above-mentioned Clogston application employing a relatively large dielectric member; and obviously other modifications of the embodiments disclosed can be made without departing from the scope of the invention as indicated in the claims.

What is claimed is:

1. In an electromagnetic wave guiding system, a conducting medium comprising a multiplicity of elongated conducting portions spaced by means including insulating material, said conducting portions and insulating material being in the form of two stacks separated by an insulating member, and magnetic material in the insulating member, and means for launching high frequency electromagnetic waves in said system, there being a sufficient number of conducting portions to carry a substantial portion of the current induced by said waves and 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 highest frequency of operation with said high frequency waves, whereby the said conducting medium is substantially penetrated by the electric field of said waves, said magnetic material being positioned substantially at points where the component of the electric field in the axial direction is at a minimum.

2. In an electromagnetic wave guiding system comprising an inner core member and an outer shell coaxially arranged therewith, a conducting medium between the core and the shell, said conducting medium comprising a multiplicity of elongated conducting portions spaced by means including insulating material, said conducting portions and insulating material being in the form of two stacks separated by an insulating member, and magnetic material in the insulating member, and means for launching high frequency electromagnetic waves in said system, there being a sufficient number of conducting portions to carry a substantial portion of the current induced by said waves and 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 highest frequency of operation with said high frequency waves, whereby the said conducting medium is substantially penetrated by the electric field of said waves, said magnetic material being positioned substantially at points where the component of the electric field in the axial direction is at a minimum.

3. The combination of elements as claimed in claim 2 in which said conducting portions and said insulating material are in the form of layers.

4. The combination of elements as claimed in claim 2 in which said magnetic material comprises a magnetic tape.

5. The combination of elements as claimed in claim 2 in which said magnetic material comprises a multiplicity of longitudinally extending tapes of magnetic material.

6. The combination of elements as claimed in claim 2 in which said stacks are coaxially arranged with respect to each other in said inner core and said outer shell.

7. The combination of elements as claimed in claim 2 in which said magnetic material comprises a cylinder.

8. The combination of elements as claimed in claim 2 in which said magnetic material comprises a plurality of spirally arranged magnetic tapes.

9. The combination of elements as claimed in claim 2 in which said magnetic material comprises a plurality of spirally arranged magnetic tapes positioned in a plurality of layers.

10. The combination of elements as claimed in claim 2 in which said magnetic material comprises a ferrite.

11. The combination of elements as claimed in claim 2 in which said magnetic material comprises a ferrite powder in insulating material.

12. The combination of elements as claimed in claim 2 in which said magnetic material comprises a ferrite cylinder.

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