

Oct. 30, 1956

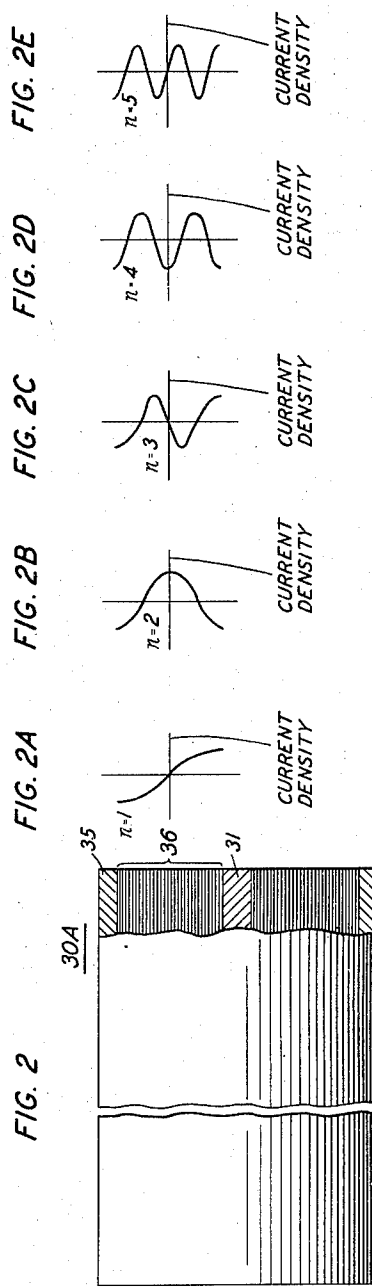
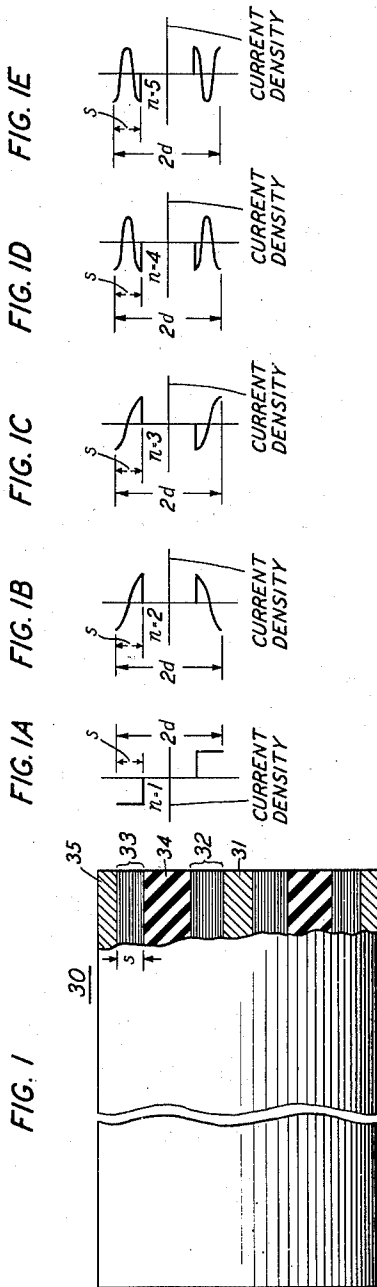
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2,769,147

WAVE PROPAGATION IN COMPOSITE CONDUCTORS

Filed May 5, 1951

4 Sheets-Sheet 1



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2,769,147

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4 Sheets-Sheet 2

FIG. 4

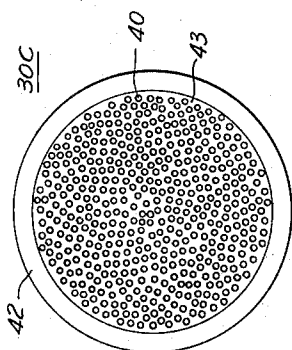


FIG. 3

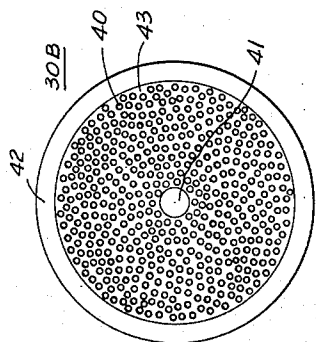


FIG. 5

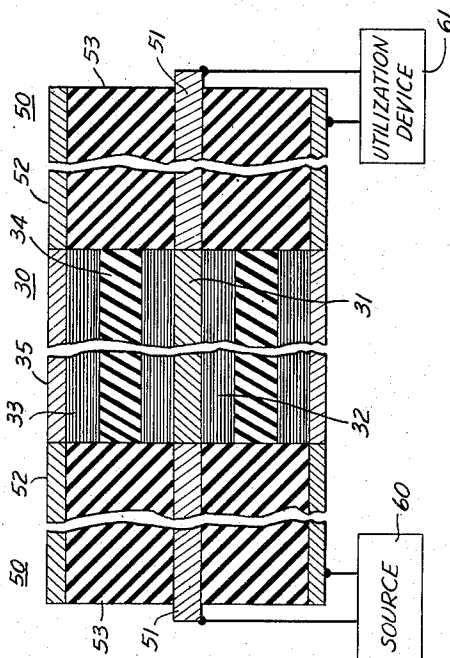
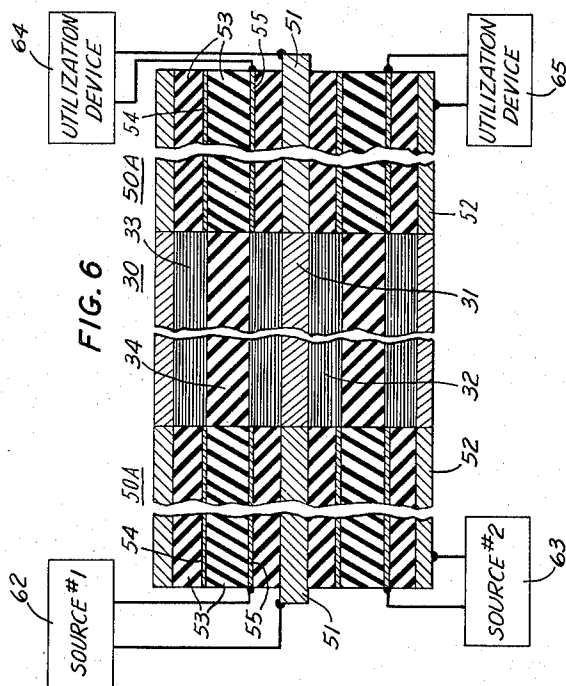


FIG. 6



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4 Sheets-Sheet 3

FIG. 8

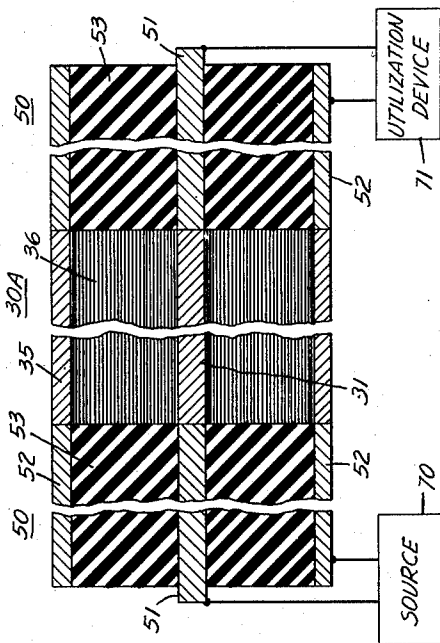


FIG. 7

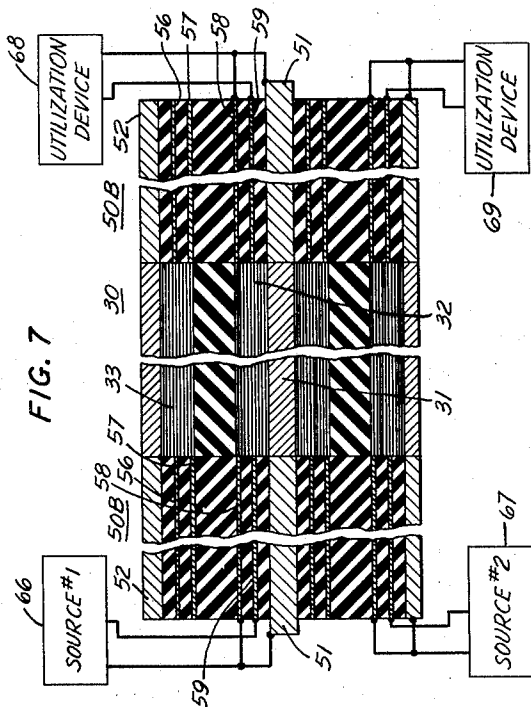


FIG. 10

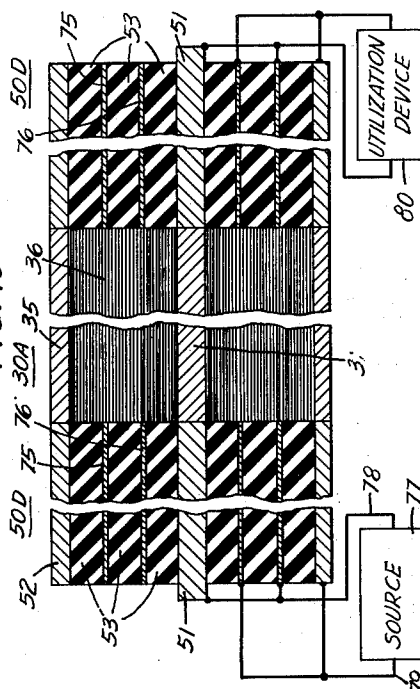
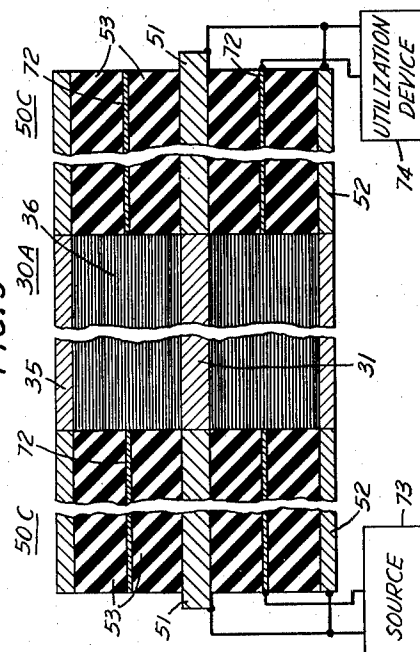


FIG. 9



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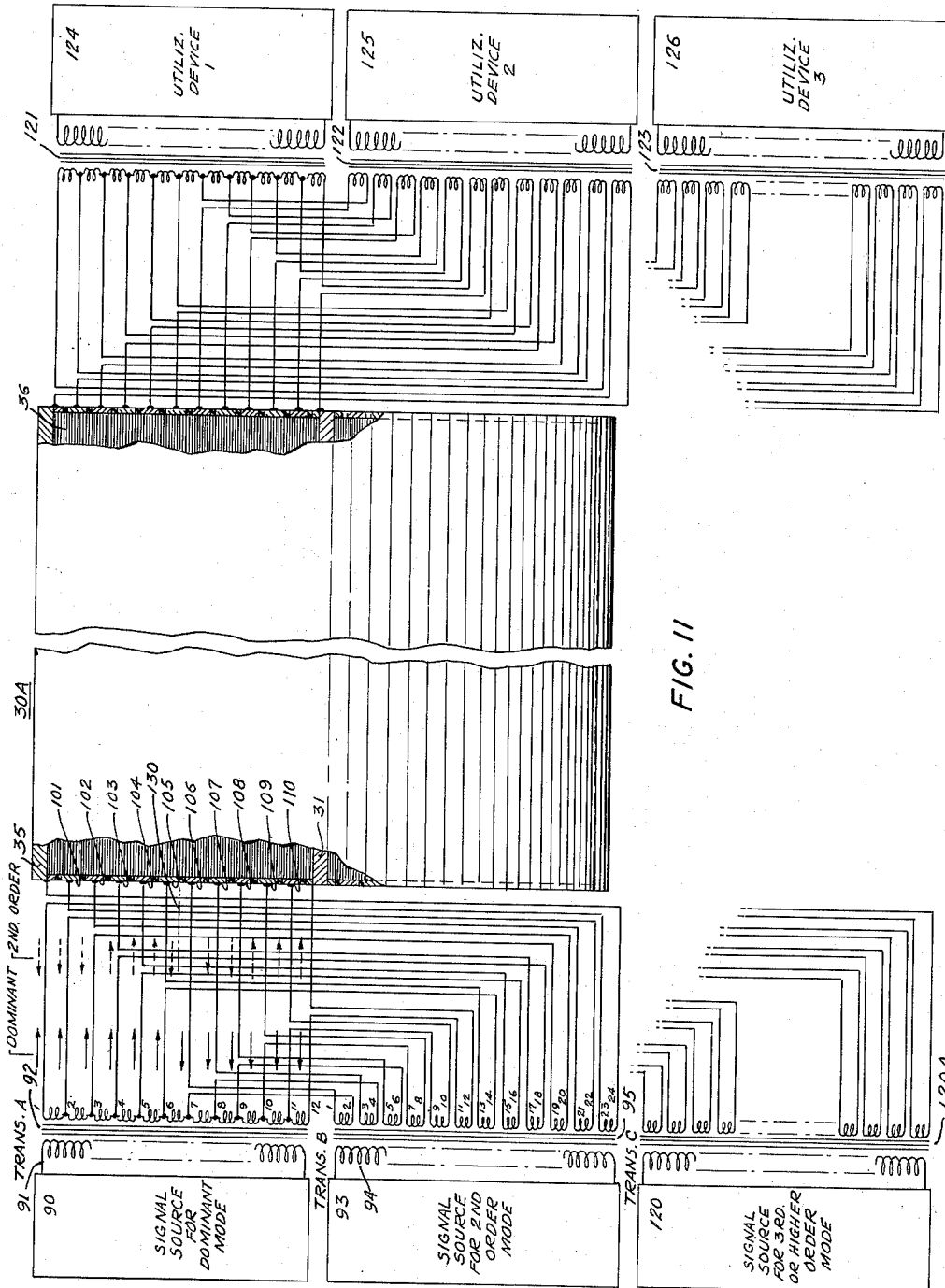
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WAVE PROPAGATION IN COMPOSITE CONDUCTORS

Filed May 5, 1951

4 Sheets-Sheet 4



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1

2,769,147

WAVE PROPAGATION IN COMPOSITE CONDUCTORS

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Application May 5, 1951, Serial No. 224,778

14 Claims. (Cl. 333—27)

This invention relates to electromagnetic wave propagating systems and more particularly to systems using composite conductors formed of a multiplicity of elongated insulated conducting portions.

It is an object of this invention to provide apparatus for exciting and utilizing electromagnetic waves propagating in modes of higher order than the principal or dominant one in electrical conductors of the composite type, such as, for example, in one of the types shown and described in the copending application of A. M. Clogston, Serial No. 214,393, filed March 7, 1951. In the present application, the term "mode" is used to indicate a space pattern of an electromagnetic field, current or voltage.

In the above-mentioned application of A. M. Clogston, 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 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 exemplary embodiment disclosed in Figs. 7A and 7B of the Clogston application, a plurality of coaxially arranged cylindrical 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 dimension 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 a factor δ which is called one skin depth. This distance is given by the expression:

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

where δ is the skin depth 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. This factor δ measures the distance in which the current or field penetrating into a slab of the metal many times δ in thickness will decrease by one neper; i. e., their amplitudes will become equal to

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

times their amplitudes 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 propagated 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 metal laminae in the

2

composite conductors. The critical velocity can be maintained by making the dielectric constant of the main dielectric i. e., 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 layer in meters. The insulating layers are also made very thin and an optimum thickness for certain structures of this general type is that in which each insulating layer is one-half of the thickness of a metal lamina. It can be seen from Equation 2 that the expression

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

is actually the average transverse dielectric constant of the laminated medium. Since, as pointed out in the aforementioned Clogston application, the velocity of propagation of an electromagnetic wave in a medium is proportional to

$$\frac{1}{\sqrt{\mu \epsilon}}$$

where μ represents the permeability of the medium and ϵ represents the dielectric constant, the velocity is the same in two different media if the product of $\mu \epsilon$ is the same for the two media, all else being equal. If the two media are adjacent each other, the velocity of propagation is substantially uniform throughout the cross-section of the area defined by the two media.

The present invention relates to the use of such a composite structure of the type just described in combination with apparatus for exciting and utilizing therein electromagnetic waves of higher order conduction current modes as distinguished from dielectric wave guide modes, and also to the excitation and utilization of such conduction current modes in other related composite conductor structures, such as, for example, others described in the above-mentioned Clogston application. As hereinafter used in the specification and claims, the term "conduction current mode" designates electromagnetic wave modes of the type wherein there is a variation in the current distribution pattern across the conductor as well as a variation in field pattern for the different modes. These modes differ from the more familiar wave guide modes which exhibit differences in field patterns for the different modes, but no differences in the current distribution pattern across the cross-section of the conductors. The conduction current mode is also characterized by the fact that it can be propagated down to zero frequencies, whereas wave guide modes are characterized by a low frequency cut-off below which the mode cannot propagate. By way of example, the invention will be described below (1) in connection with a composite structure of the type just described in detail, (2) in connection with a variation which is shown in Fig. 17A of the above-mentioned Clogston application and which is similar to the embodiment just described in detail except for the fact that the dielectric member between the two composite conductors is completely filled with alternate metal and insulating laminae, thus forming in essence one large cylindrical stack of insulated metal laminae, and (3) in connection with a variation of these embodiments in which a multiplicity of tiny elongated filaments are used in place of the metal laminae and which is described in greater detail in connection

with Figs. 18A and 18B of the above-mentioned Clogston application. It will be understood, however, and clearly obvious to one skilled in the art, that the invention is not limited to combinations utilizing the above-mentioned specific structures since it can be readily applied to other structures of the composite type mentioned in the above-identified Clogston application and to other modifications employing the same principles.

In any of the composite conductors described above, there exist a multiplicity of modes of transmission in which the fundamental, principal or dominant mode with propagation constant k_0 corresponds to the ordinary mode of transmission that would exist between a pair of parallel spaced plates. The higher modes are waves that are confined almost entirely to the laminations (or filaments) and are not encountered in an ordinary transmission line. They have many interesting properties. The waves propagating in all the modes travel at nearly the same speed and may include waves down to zero frequency. The highest frequency which can be transmitted, however, increases as the mode number increases. Moreover, the attenuation of the waves increases as the mode number increases. By way of example, the second order mode has an attenuation much greater than that of the fundamental mode, the attenuation of the third order mode is again greater than that of the second order modes, and the attenuation of the fourth order mode is still greater than that of the third order mode. In the description that follows, it will be pointed out how various modes can be excited and utilized in a composite conductor to the exclusion of other modes and also an arrangement will be shown and described in which waves operating in a plurality of modes are independently and simultaneously propagated and utilized in composite conductor systems.

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 a longitudinal view, with portions broken away, of a coaxial transmission line of the type shown in Fig. 7B of the above-mentioned Clogston application and in which waves of various modes are excited in accordance with the invention;

Figs. 1A to 1E, inclusive, show approximate current density patterns of the fundamental, second, third, fourth and fifth modes, respectively, in a transmission line of the type shown in Fig. 1;

Fig. 2 is a longitudinal view, with portions broken away, of a coaxial transmission line of the type shown in Fig. 17A of the above-mentioned Clogston application and in which waves of various modes are excited in accordance with the invention;

Figs. 2A to 2E, inclusive, show approximate current density patterns of the fundamental, second, third, fourth and fifth modes, respectively, in a transmission line of the type shown in Fig. 2;

Figs. 3 and 4 are end views of composite conductors of the types shown in Figs. 18A and 18B, respectively, of the above-mentioned Clogston application and in which waves operating in the modes shown in Figs. 2A to 2E, inclusive, can be propagated in accordance with the invention;

Figs. 5, 6 and 7 are longitudinal sectional views, with portions broken away, of a composite conductor of the type shown in Fig. 1 and input and output terminal connections therefor for exciting therein and removing therefrom waves operating in the principal mode, second and third modes, and fourth and fifth modes, respectively;

Figs. 8, 9 and 10 are longitudinal sectional views, with portions broken away, of a composite conductor of the type shown in Fig. 2 and input and output terminal connections therefor for exciting therein and removing therefrom waves operating in the principal mode, second mode, and third mode, respectively; and

Fig. 11 is a schematic diagram of a composite conductor

of the type shown in Fig. 2 and circuit connections for applying thereto and removing therefrom simultaneously and independently a plurality of modes propagating in different modes.

Referring more particularly to the drawings, Fig. 1 shows, by way of example for purposes of illustration, a conductor 30 in which, in accordance with the invention, various waves operating at different modes can be propagated. The conductor 30 comprises a central core 31 (which may be either of metal or dielectric material), a cylindrical inner conductor or stack 32 formed of many laminations of metal spaced by insulating material, a cylindrical outer conductor or stack 33 similarly formed of a multiplicity of layers of metal spaced by insulating material and separated from the inner conductor 32 by an annular dielectric member 34, and an outer sheath 35 of metal or other suitable shielding material. As disclosed in the above-mentioned Clogston application, the metal layers in the composite conductors 32 and 33 are each very thin compared to the skin depth of the conducting material being used, which, for example, can be copper, silver or aluminum. The insulating layers in the composite conductors 32 and 33 are also made very thin and may be of any suitable material. Preferably, they 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 32 has perhaps 10 to 100 or more metal layers and the outer conductor 33 has a somewhat similar number of metallic layers although there need not be exactly the same number as in the inner conductor 32. 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 (32 or 33) is of metal or of insulation. For a wide band of frequencies, the dielectric material 34 is preferably chosen so that the velocity of propagation of a wave going down the length of the conductor has the proper value to give minimum attenuation, as set forth in the above-identified Clogston application. Equation 2 given above sets forth the relationship between ϵ_1 , which is the dielectric constant of the member 34, and ϵ_0 , which is the dielectric constant of the insulating material in the stacks 32 and 33, in terms of the thickness W of the metal laminae and of the thickness t of the insulating material therebetween. For a more detailed description of the conductor shown in Fig. 1, reference is made to the description in the above-identified Clogston application, special reference being made to Fig. 7B.

As pointed out above, there can be set up in the conductor 30 simultaneously and independently electromagnetic waves propagating in respectively different conduction current modes. Figs. 1A to 1E, inclusive, show approximate typical patterns of a fundamental mode (Fig. 1A), a second order mode (Fig. 1B), a third order mode (Fig. 1C), a fourth order mode (Fig. 1D), and a fifth order mode (Fig. 1E). While there is a large number of modes that can be transmitted in a conductor such as that shown in Fig. 1, actually, as a practical matter, only a moderate number of the lower order modes will be used due to the fact that the attenuation of the higher modes is much higher than that of the fundamental and increases as the order of mode increases. In each of Figs. 1A to 1E, inclusive, the horizontal dimension represents current density while the vertical dimension represents radial distance, the overall distance shown as $2d$ in the drawing being equal to the overall distance between the inside surface of the shield 35 and the outside surface of the core 31. It will be noted that the fundamental (Fig. 1A), the third order mode (Fig. 1C) and the fifth order mode (Fig. 1E) have an odd order symmetry with respect to the vertical center line whereas the curves for the second and fourth order modes (Figs. 1B and 1D) have even order symmetry with respect to this vertical center line. The modes shown in Figs. 1A

to 1E, inclusive, transmit successively broader frequency bands, and this factor can be utilized in multiplexing.

Fig. 2 is a longitudinal view with portions broken away of a cable 30A like that shown in Fig. 1 except that the space occupied by the cylindrical dielectric member 34 of the conductor 30 in Fig. 1 is filled up with insulated laminations so that, in effect, the members 33, 34 and 32 of the conductor 30 are replaced by a single cylindrical stack 36 of alternate metal and insulating laminae of the same general dimensions as those in the conductor 30. For a more detailed description of the conductor shown in Fig. 2, reference is made to the above-identified Clogston application with specific reference to Fig. 17A.

Figs. 2A to 2E, inclusive, show mode patterns for the conductor 30A for the fundamental mode (Fig. 2A), the second order mode (Fig. 2B), the third order mode (Fig. 2C), the fourth order mode (Fig. 2D) and the fifth order mode (Fig. 2E). In each case, the mode numbers are indicated by the number set equal to n in the drawing.

The modes of Figs. 1A to 1E, inclusive, can now be compared to Figs. 2A to 2E, inclusive, respectively. Clearly, there is a one to one correspondence of the modes since the partially filled conductor 30 of Fig. 1 can be made to approach the completely filled conductor 30A of Fig. 2 continuously by adding more laminated material. The correspondence can be seen by comparing Fig. 1A to Fig. 2A, Fig. 1B to Fig. 2B, Fig. 1C to Fig. 2C, Fig. 1D to Fig. 2D and Fig. 1E to Fig. 2E.

Figs. 3 and 4 are end views of composite conductors 30B and 30C similar to conductor 30A in Fig. 2 except that instead of laminations a multiplicity of tiny filaments 40 of diameter small compared to a skin depth are used. Fig. 3 differs from Fig. 4 in that a central core 41 is employed and each of conductors 30B and 30C utilizes an outer shield 42 corresponding to the shield 35 of Figs. 1 and 2. The metal filaments 40 are spaced by insulating material 43. For more detailed descriptions of the conductors 30B and 30C reference is made to the above-identified Clogston application with special reference to Figs. 18A and 18B, respectively. The mode patterns of the conductors 30B and 30C are like those for the conductor 30A of Fig. 2 so will not be repeated. The various modes can be set up in the conductors 30B and 30C in a manner similar to that which is used in propagating the waves in the conductor 30A to be described below.

Figs. 5, 6 and 7 illustrate means for applying and removing electromagnetic waves propagating in the fundamental, second and third modes, and fourth and fifth modes, respectively, in a conductor 30 of the type shown in Fig. 1, that is, a cable of the "partially filled" type. It is to be understood that in each of Figs. 5, 6 and 7 the conductor 30 may be a cable of relatively great length such as, for example, of the order of miles, or it may be relatively short (a matter of inches or feet). Each end of the cable 30 is terminated by butting it against a coaxial cable 50 having an inner conductor 51 in contact with the inner conductor 31, an outer conductor 52 in contact with the outer shield 35 and dielectric member 53 completely filling the space between the conductors 51 and 52 and having a value of dielectric constant equal to that given in the expression for ϵ_1 given in Equation 2 above. If the central core 31 of the cable 30 is of dielectric rather than of metallic material the conductor 51 is made large enough or the end thereof near the conductor 30 enlarged to such an extent that contact is made to at least one of the metal laminae in the inner composite conductor 32. A source 60 of signal voltage (which may comprise a wide band of frequencies or a single frequency of high or low value) is applied between the outer and inner conductors 52 and 51 of the input cable 50 and waves operating in the fundamental mode are propagated in the cable 30 and assume the space pattern shown in Fig. 1A. These waves of the funda-

mental mode can be removed from the output cable 50 by connecting a utilization device 61, such as the input resistor of a suitable amplifier, for example, between the conductors 51 and 52 of this cable.

Fig. 6 shows an arrangement wherein the second and third order modes (Fig. 1B) are set up in the conductor 30 and removed therefrom. The input and output cables 50A are like the cables 50 of Fig. 5 except that they have two annular rings 54 and 55 placed to contact the innermost laminae of the stack 33 and the outermost laminae of the stack 31, respectively. Each annular ring is wide compared to a skin depth. A first source 62 is applied between the ring 55 and the inner conductor 51 of the input cable 50A while a second source 63 is applied between the outer annular ring 54 and the outer conductor 52 of the cable 50A. With use of the proper phase and magnitude of the voltage of the source 62 with respect to that of the signal of the source 63, the mode shown in Fig. 1B (called the second mode) or that shown in Fig. 1C (called the 3rd mode) can be established. These signals can be removed from the cable 30 by means of the righthand or output cable 50A (by connecting suitable utilization devices 64 and 65 to the members of the right-hand cable 50A similar to the connections for the sources 62 and 63 to the left-hand cable 50A). It will be readily apparent that two entirely different signals can be sent in the arrangement of Fig. 6.

The arrangement shown in Fig. 7 is similar to that shown in Fig. 6 except that four annular rings 56, 57, 58 and 59 are used in the input and output cables 50B instead of the two rings 54 and 55 in the cables 50A of Fig. 6. The ring 56 contacts substantially the center of the stack 33, the ring 57 contacts the lower portion of stack 33, the ring 58 contacts the upper portion of the stack 32, and the ring 59 contacts the middle portion of stack 32. The source 66 is applied between the annular ring 59 and the inner conductor 51 of the input cable 50B. This conductor 51 is also connected to the annular ring 58. The source 67 is connected between the outer conductor 52 of the input cable 50B and the annular ring 56, the ring 57 being also connected to the conductor 52. By means of this arrangement, wave shapes of the type shown in Fig. 1D or Fig. 1E, in any proportion, can be obtained by varying the phase and amplitude of the signal source 66 and 67. Utilization devices 68 and 69 connected to the output cable 50B similarly to the way in which the sources 66 and 67 are connected to the input cable 50B can be used to remove the waves applied to the input end of the cable 30.

Figs. 8, 9 and 10 show arrangements in connection with the conductor 30A of Fig. 2 for launching and removing electromagnetic waves propagating in the modes shown in Figs. 2A, 2B and 2C, respectively. The input and output cables 50 are similar to the input and output cables 50 shown in Fig. 5, the dielectric member 53 having a dielectric constant which is equal to the average dielectric constant of the stack 36 of the cable 30A. The source 70 applied between the conductors 51 and 52 excites a wave operating at the fundamental mode and this wave is removed from the cable 30A by connecting the utilization device 71 between the conductors 51 and 52 of the output (right-hand) cable 50.

Fig. 9 shows an arrangement for exciting a wave operating in the second order mode shown in Fig. 2B. This arrangement employs two cables 50C connected to respectively opposite ends of cable 30A. Each cable 50C is like the cable 50 except that it has an annular ring 72 therein substantially in the middle of the stack 36 of the cable 30A. To cause the excited wave to propagate in the second order mode as shown in Fig. 2B, the source 73 is connected between the inner conductor 51 of the cable 50C and the annular ring 72 thereof, the outer conductor 52 being also connected to the inner conductor 51. To remove this wave from the conductor 30A, a suitable

utilization device 74 is connected to the output cable 50C in a manner similar to the connection of the source 73 to the input cable 50C.

Fig. 10 shows an arrangement for utilizing a wave propagating in the third order mode as shown in Fig. 2C in the cable 30A. The input and output cables 50D are connected to the respective ends of the cable 30A, and these cables are similar to cable 50 except that two annular rings 75 and 76, respectively, are placed in contact with the axis from stack 36 so as to divide the space between the inner terminal 51 and the outer terminal 52 approximately into thirds. Terminal 78 of the source 77 is connected to the ring 75 and to the inner conductor 51, while terminal 79 of the source 77 is connected to the outer conductor 52 and the ring 76. The utilization device 80 is connected to the output cable 50D in a manner similar to that in which the source 77 is connected to the input cable 50D.

In all of the arrangements described above, the annular rings in the cables 50A to 50D inclusive, preferably have a thickness which is several times skin thickness. Also with respect to Figs. 8 to 10, inclusive, cables of the type shown in Figs. 3 and 4 can be used in place of the cable 30A, the input and output cables being similar to those used with the cable 30A.

Fig. 11 shows an arrangement for multiplexing using a plurality of modes simultaneously and independently. A signal source 90 for the dominant mode is applied to the primary winding 91 of the transformer 92, the output winding of which is split up into a number of coils, for example, 1-2, 2-3, 3-4, 5-6 . . . 11-12. Another signal source 93 is connected to the input winding 94 of the second transformer 95 having a multiplicity of separated windings 1-2, 3-4 . . . 23-24. The secondary windings of the transformers 92 and 95 are connected as shown in the drawing to the outer and inner terminals 35 and 31 respectively, of a conductor 30A and to a multiplicity of metallic annular rings 101, 102, 103, 104, 105, 106, 107, 108, 109, 110 . . . therebetween, each annular ring 101, 102, etc. being wide enough to contact the ends of a plurality of metal laminae in the stack 36. The various secondary coils are wrapped to produce current in the annular rings in the proper relative directions as indicated in the full line arrows for the dominant mode current and the dotted line arrows for the second mode current. It will be noted that the connections are made in such a manner that the proper phase reversals are obtained so that a signal of the dominant mode and also one of the second order mode are propagated simultaneously in the cable 30A and also due to the arrangement of windings (that is, the effect of one winding is to cancel out the other in certain instances), none of the dominant mode signal appears in the primary winding of the transformer 95 and none of the second order mode signal appears in the primary mode winding of the transformer 92. Similarly, a signal source 120 for the third order, or higher mode, can be connected to the cable 30A through transformer 120A in a manner which will be obvious to one skilled in the art in view of the circuitry for transformers 92 and 95. The transformers 121, 122, 123, etc., respectively, connected to utilization devices 124, 125 in a manner similar to the connection of the signal sources 90, 93 and 120 in the input end are used to remove the signals operating at the various modes.

It is obvious that the arrangement of Fig. 11 can be used with a conductor 30 of Fig. 1, the connections above the dotted line 130 being applied to annular rings for the outer stack 33 and those below the dotted line 130 being applied to rings for the inner stack 32. Moreover the arrangement of Fig. 11 is applicable without change to conductors of the types shown in Figs. 3 and 4.

Although it is theoretically possible to determine by mathematical analysis the proper relative turns ratios among the different windings comprising each mode trans-

former, in practice it is simpler and better to determine this experimentally. A length of laminated cable is successively excited (as in Figs. 8 to 10, inclusive) to each mode of interest in turn. At the other end which may be open (high impedance termination) annular rings (such as rings 101 to 110 of Fig. 11) are utilized and form a fixed excitation at the sending end, the voltages of interest are measured with a high impedance voltmeter. The number of turns on the input winding is so adjusted that this winding presents the desired impedance to the signal source. If it is desired to keep the length of cable to a minimum the above experimental determination can be carried out by using the cable as a half-wavelength resonator. In this case, the sending end termination is also of very high impedance which means the exciter (cable 50, 50A etc.) is very loosely coupled to the cable.

The invention has a number of advantages. For example, even though the higher modes are attenuated more rapidly than the fundamental mode, the invention is useful in an arrangement where a signal cable of type 30 or 30A, for example, exists (and it is not practical to install another one) when it is desired to send one or more additional signals independently and simultaneously with the first. Another advantage lies in the fact that a conductor operating at the higher modes will transmit a wider frequency band than when operated at the lower order modes, thus providing more channels than the dominant mode.

It is obvious that the invention is not restricted to the specific arrangements shown as obviously other modifications can be made in the embodiments described above without departing from the scope of the invention as indicated in the claims.

What is claimed is:

1. In combination, a composite electromagnetic wave conductor comprising a multiplicity of elongated conducting portions separated by insulating material, said conducting and insulating portions being so dimensioned relative to each other and the dielectric constant of the insulating material being such that the conductor can propagate a plurality of conduction current modes of different order, means for applying to said conductor electromagnetic waves propagating in a conduction current mode of a higher order than the principal one, and means for utilizing the waves of said higher order mode.

2. In combination, a composite electromagnetic wave conductor comprising a multiplicity of concentric layers of conducting material separated by insulating material and in which all of the layers within the composite conductor are substantially evenly spaced from adjacent ones, said conducting layers and said insulating material being so proportioned relative to each other and the dielectric constant of the insulating material being such that the conductor can propagate a plurality of conduction current modes of different order, means for applying to said conductor electromagnetic waves propagating in a conduction current mode of a higher order than the principal one, and means for utilizing the waves of said higher order mode.

3. In combination, a medium for the transmission of electromagnetic waves comprising two coaxially arranged composite conductors separated by dielectric material, each composite conductor being circular in cross section and each comprising a composite stack of insulated concentric thin-walled conducting cylinders, said conducting cylinders and the insulation being so dimensioned and the dielectric constant of the insulating material being such that the medium can propagate a plurality of conduction current modes of different order, means for applying to said medium electromagnetic waves propagating in a conduction current mode of a higher order than the principal one, and means for utilizing the waves of said higher order mode.

4. In combination, a cable comprising a central wall and an outer shell and means between the wall and the

shell for the conduction of current, said means comprising a multiplicity of very thin conducting layers separated by very thin insulated layers, said conducting and insulating layers being so dimensioned and the dielectric constant of the insulating layers being such that the cable can propagate a plurality of conduction current modes of different order, means for applying to said composite conductor electromagnetic waves propagating in a conduction current mode of higher order than the principal one, and means for utilizing the waves of said higher order mode.

5. In combination, a composite electromagnetic wave conductor comprising a multiplicity of elongated metallic filaments spaced by insulating material, said filaments being so dimensioned and the dielectric constant of the insulating material being such that the conductor can propagate a plurality of conduction current modes of different order, means for applying to said conductor electromagnetic waves propagating in a conduction current mode of a higher order than the principal one, and means for utilizing the waves of said higher order mode.

6. In combination, a composite electromagnetic wave conductor comprising a multiplicity of elongated conducting portions spaced by insulating material, said conducting and insulating portions being so dimensioned relative to each other and the dielectric constant of the insulating material being such that the conductor can propagate a plurality of conduction current modes of different order, means for applying to said conductor simultaneously and independently electromagnetic waves propagating in different order conduction current modes, and means for utilizing any of said waves to the exclusion of any other one.

7. In combination, a composite electromagnetic wave conductor comprising a multiplicity of elongated conducting portions spaced by insulating material, said conducting and insulating portions being so dimensioned relative to each other and the dielectric constant of the insulating material being such that the conductor can propagate a plurality of conduction current modes of different order, means for applying to said conductor simultaneously and independently electromagnetic waves propagating in different order conduction current modes, and means for utilizing all of said waves independently.

8. In combination, a composite electromagnetic wave conductor comprising a multiplicity of elongated conducting portions spaced by insulating material, said conducting and insulating portions being so dimensioned relative to each other and the dielectric constant of the insulating material being such that the conductor can propagate a plurality of conduction current modes of different order, means for applying to said conductor electromagnetic waves propagating in the principal mode, means for applying to said conductor electromagnetic waves propagating in a conduction current mode of a higher order than the principal one, and means for removing said waves of the principal mode and of said higher order mode from said conductor independently of one another.

9. The combination of elements as in claim 8 in which said applying means and removing means comprise transformer means.

10. A wave transmission system comprising a composite electromagnetic wave conductor including a multiplicity of elongated conducting portions separated by insulating material the thickness of each conducting portion being less than the skin depth of penetration of waves at the highest frequency of operation of said system, the thickness of the insulating material between the conducting portions being so proportioned relative to the conducting portions and the dielectric constant of the insulating material being such that the conductor can propagate a plurality of conduction current modes of different order, means for applying to said conductor electromagnetic waves propagating in a conduction current mode of a

higher order than the fundamental one, and means for utilizing the waves of said higher order mode.

11. A wave transmission system comprising a composite electromagnetic wave conductor capable of propagating a plurality of conduction current modes of different order and having a multiplicity of elongated conducting portions separated by insulating material, there being a sufficient number of conducting portions to carry a significant fraction of the total current, the thickness of each of said conducting portions being less than a skin depth of penetration of the highest frequency of operation of said system, means including said conducting portions and said insulating material for causing the propagation velocity of an electromagnetic wave in said conductor to be substantially uniform across the cross-sectional area of the conductor, means at one end for applying to said conductor electromagnetic waves propagating in a conduction current mode of a higher order than the fundamental one, and means at the other end for utilizing the waves of said higher order mode.

12. A wave transmission system comprising a composite electromagnetic wave conductor capable of propagating a plurality of conduction current modes of different order and having inner and outer conducting members and a multiplicity of elongated conducting portions separated by insulating material between said inner and outer members, there being a sufficient number of conducting portions to carry a significant fraction of the total current, the thickness of each of said conducting portions being less than a skin depth of penetration of the highest frequency of operation of said system, means including said conducting portions and said insulating material for causing the propagation velocity of an electromagnetic wave in said conductor to be substantially uniform across the cross-sectional area of the conductor, means at one end for applying to said conductor electromagnetic waves propagating in a conduction current mode of a higher order than the fundamental one, and means at the other end for utilizing the waves of said higher order mode.

13. A wave transmission system as claimed in claim 11 wherein the means for applying electromagnetic waves to the conductor comprises a source of signal voltage and means connecting said source to the inner conducting member and to at least one of said elongated conducting portions which lies intermediate the inner and outer conducting members.

14. A wave transmission system as claimed in claim 13 wherein the means connecting the source comprises a coaxial cable having inner and outer conducting members contacting the inner and outer conducting members of the composite conductor and an intermediate conducting member contacting at least one of said conducting portions, said source being electrically connected to the inner and intermediate conducting members of said coaxial cable.

References Cited in the file of this patent

UNITED STATES PATENTS

1,701,278	Silbermann	Feb. 5, 1929
1,855,303	McCurdy	Apr. 26, 1932
2,088,749	King	Aug. 3, 1937
2,129,711	Southworth	Sept. 13, 1938
2,191,995	Scott	Feb. 27, 1940
2,231,602	Southworth	Feb. 11, 1941
2,257,783	Bowen	Oct. 7, 1941
2,267,289	Roosenstein	Dec. 23, 1941
2,676,309	Armstrong	Apr. 20, 1954

OTHER REFERENCES

Microwave Transmission Design Data, Sperry Gyroscope Co., Publications Dept., Great Neck, Long Island, page 7. (Received in Patent Office Library Feb. 18, 1946.) Copy in Div. 69.