

July 9, 1957

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2,799,006

MULTIPLEXING VARIOUS MODES IN COMPOSITE CONDUCTORS

Filed March 24, 1953

4 Sheets-Sheet 1

FIG. 1

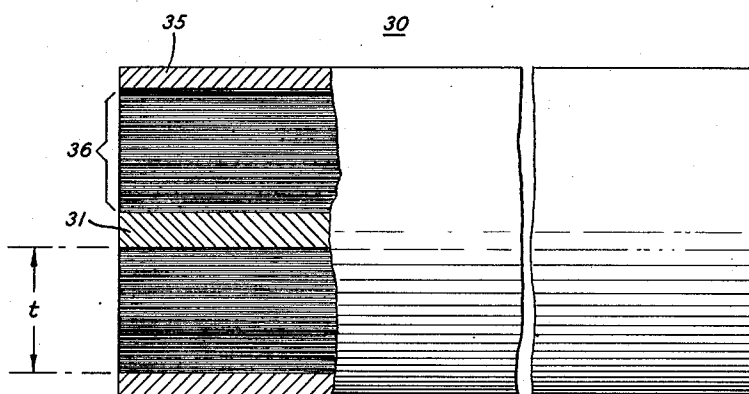


FIG. 1A

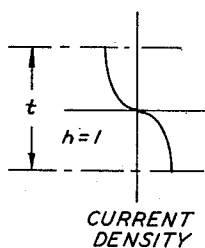


FIG. 1B

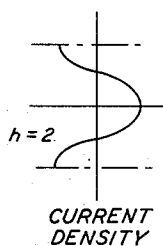


FIG. 1C

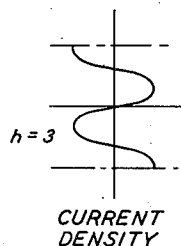


FIG. 1D

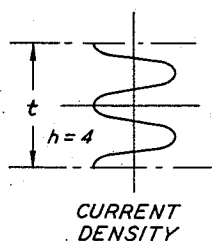
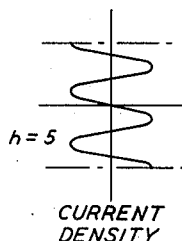


FIG. 1E



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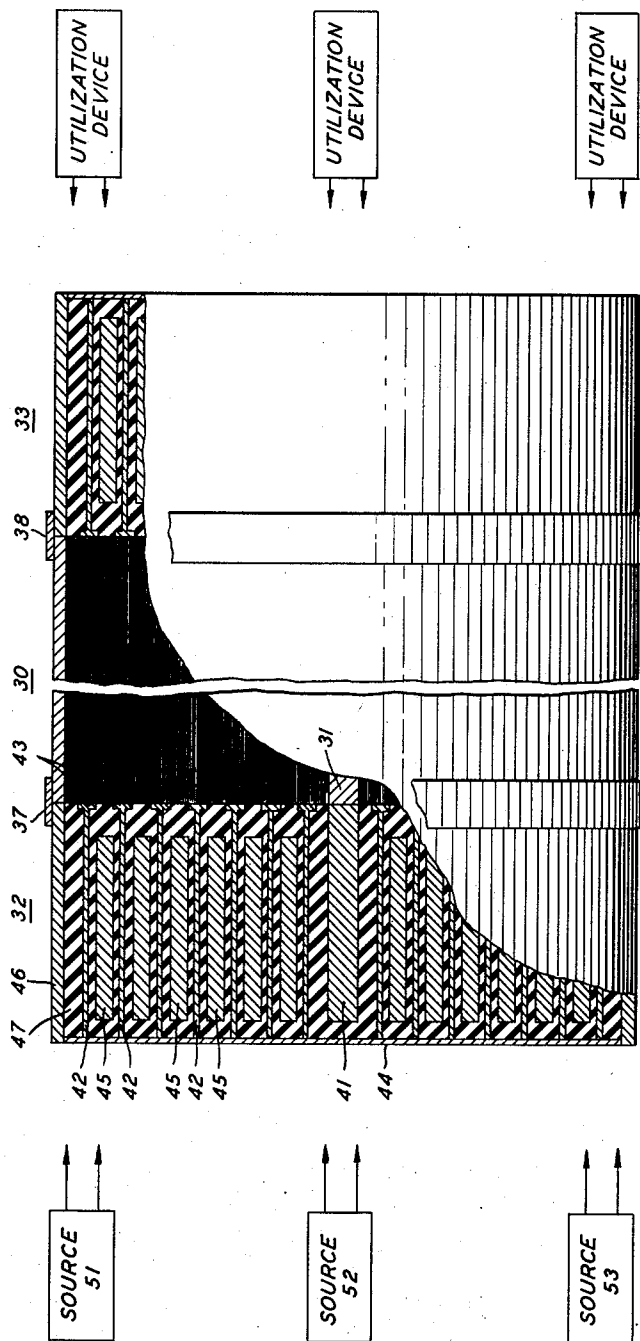
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FIG. 2



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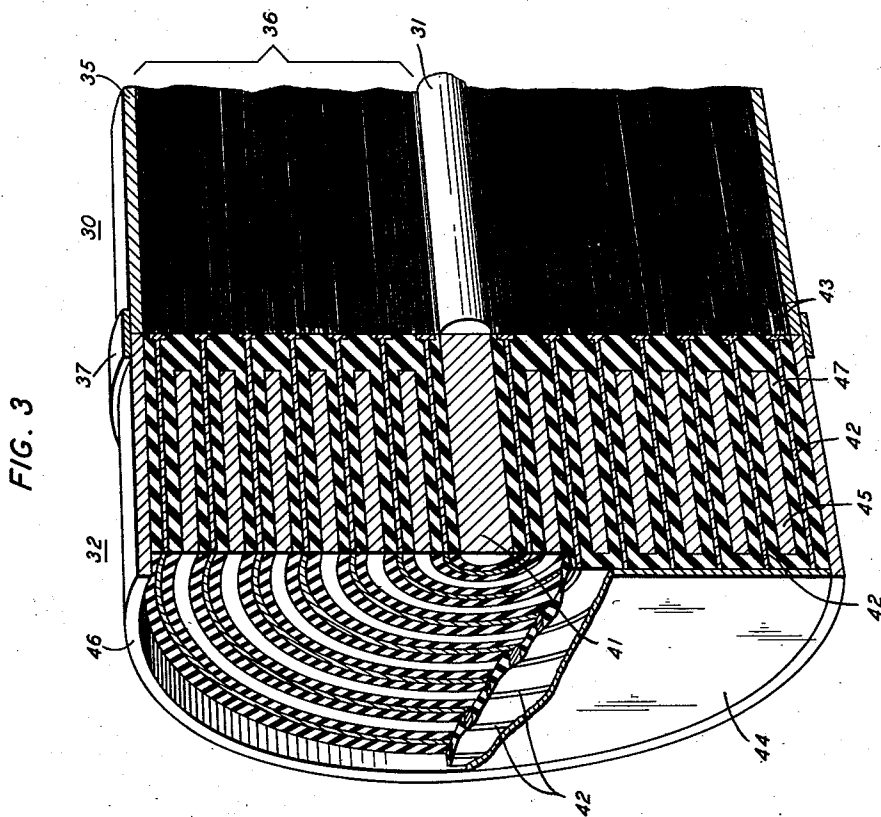
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MULTIPLEXING VARIOUS MODES IN COMPOSITE CONDUCTORS

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MULTIPLEXING VARIOUS MODES IN COMPOSITE CONDUCTORS

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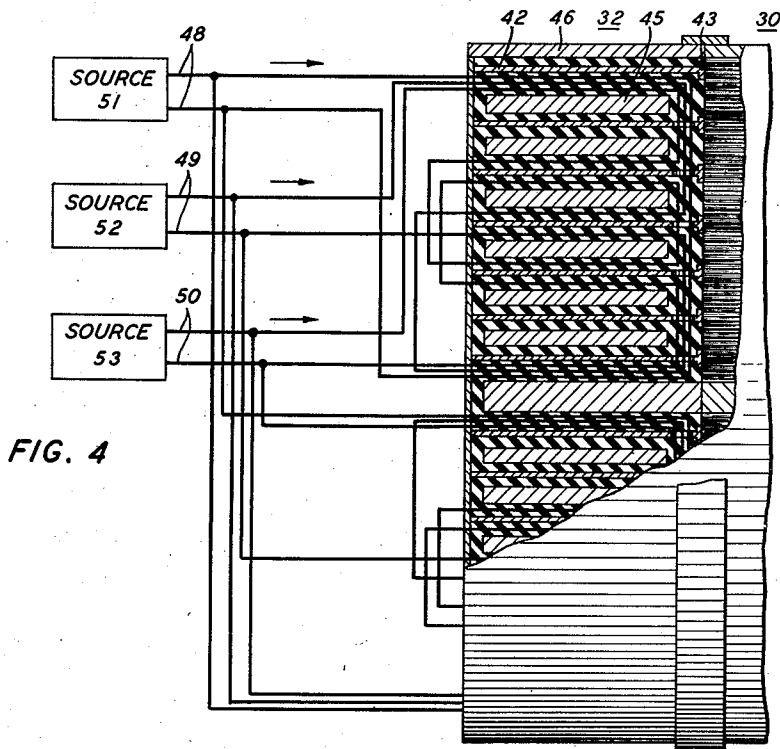
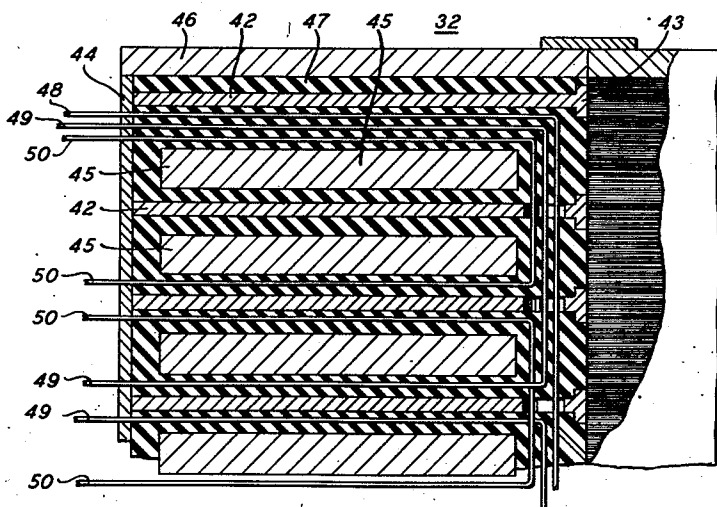


FIG. 4

FIG. 5



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MULTIPLEXING VARIOUS MODES IN COMPOSITE CONDUCTORS

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Application March 24, 1953, Serial No. 344,437

3 Claims. (Cl. 333—24)

This invention relates to electromagnetic wave propagating systems and, more specifically, to systems using composite conductors formed of a multiplicity of elongated insulated metal laminae.

It is an object of this invention to provide apparatus for exciting and utilizing electromagnetic waves propagated in the fundamental mode and in modes of higher order than the fundamental in electric conductors of the laminated type, such as, for example, in one or more of the types shown and described in the copending application of A. M. Clogston, Serial No. 214,393, filed March 7, 1951, now Patent 2,769,148, October 30, 1956. In the present application, the term "mode" is used to indicate a space pattern of an electromagnetic field, current, or voltage.

It is another object of this invention to provide novel transforming means for applying electromagnetic waves to laminated conductors and for removing such waves therefrom.

In the above-mentioned patent 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 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 exemplary embodiment disclosed in Fig. 17A of the Clogston patent, the composite conductor comprises a multiplicity of thin metal laminations, insulated from each other 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 1,000 times) smaller than a factor δ which is called one-skin depth. This distance is given by the expression:

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

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

$$\frac{1}{e}$$

or 0.3679 . . . times their amplitudes at the surface of the slab.

It is pointed out in the above-mentioned Clogston patent that when a composite 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

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(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 composite laminated conductors. 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.

The present invention relates to transformer means for applying waves to and removing waves from structures of the laminated type described above. More specifically, the transformer means operates to apply electromagnetic waves of the fundamental mode and of higher modes and to remove such waves from the composite conductor. The transformer has two principal windings and a core, and comprises a multiplicity of tubular metallic laminations coaxially spaced apart from one another by a greater distance than the metallic laminations in the Clogston cable to which it is connected. Between each metallic lamination is a tube of ferromagnetic material. All of these tubes collectively comprise the core of the transformer. One end of each of the conducting laminations is short circuited to each of its neighboring conducting laminations while the opposite end of each of the laminations is connected to an annular ring which contacts a multiplicity of laminations in the Clogston cable abutting the transformer. Each two adjacent connected metallic laminations comprise the equivalent of a single thin sheet of conductor enclosing a single magnetic lamination and all of the single sheet conductors taken together comprise the first principal winding of the transformer. Such single thin sheets are connected coaxially to the adjacent groups of conducting laminations in the laminated transmission line by the annular metallic rings. Insulated wires wound around the magnetic laminations or groups thereof comprise the second principal winding of the transformer. There may be a plurality of individual second windings and the number of loops in each individual winding and the arrangement of the loops thereof with respect to the magnetic laminations are determined so as to conform with the magnetic field characteristic of the electromagnetic wave desired to be applied to or removed from the line by each individual second winding. In the description that follows, it will be pointed out how various modes can be applied to and removed from a composite conductor to the exclusion of other modes and also how a plurality of modes are independently and simultaneously applied to and removed from a composite conductor.

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. 17A of the above-mentioned Clogston patent and in which waves of various modes can be transmitted;

Figs. 1A to 1E, inclusive, show approximate current density patterns of the fundamental, second, third, fourth and fifth order 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. 1 with input and output transformers in accordance with the invention connected to the ends thereof;

Fig. 3 is a sectional view, in perspective, of one of the transformers and the associated transmission line shown in Fig. 2;

Fig. 4 is a schematic diagram of the input transformer

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of Fig. 2 showing the transformer connected to sources of current in accordance with the invention; and

Fig. 5 is a sectionalized view of a portion of the transformer of Fig. 4 showing its elements in enlarged detail.

Referring more particularly to the drawings, Fig. 1 shows by way of example a conductor 30 in which various waves operating in different modes can be propagated. The conductor 30 comprises a central rod 31 which may be of either metal or dielectric material, a cylindrical composite conductor or stack 36 having a thickness t formed of many laminations of metal spaced by insulating material and an outer sheath 35 of metal or other suitable shielding material. As described in the above disclosed Clogston patent, the metal layers in the composite conductor 36 are very thin compared with the skin depth of the conducting material used which can be copper, silver or aluminum. The insulating layers in the composite conductor 36 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.

As pointed out above, there can be set up in the conductor 30 simultaneously and independently electromagnetic waves propagating in respectively different modes. Figs. 1A to 1E, inclusive, show approximate current density patterns characteristic 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 no limit to the 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 greater than that of the fundamental and increases as the order of the mode increases. The modes shown transmit successively broader frequency bands and this factor can be utilized in multiplexing. In each of Figs. 1A to 1E, inclusive, the horizontal dimensions represent current density while the vertical dimension represents the radial dimension t of the composite conductor 36 as shown in Fig. 1 measured from the inside surface of the shield 35 to the outside surface of the rod 31. In each case the mode number is indicated by the number in the drawing set equal to h .

Fig. 2 shows a structural view of the transformers in accordance with the invention coupled to the coaxial transmission line 30 of Fig. 1. For purposes of easier understanding and easier reading of the drawings, the second principal winding in the transformers is omitted in Fig. 2 and in Fig. 3 and is shown combined with the transformer in Figs. 4 and 5. An input transformer 32 is shown in Fig. 2 connected to one end of the line 30 by a band 37 and an output transformer 33 which is identical in structure to transformer 32, is shown connected to the other end of the line 30 by a band 38. The transformers 32 and 33 each comprise a central rod 41 which may be of metal or dielectric material similar to that of rod 31, a multiplicity of metal tubes 42 coaxial with the central rod 41, ferromagnetic tubes 45 spaced between the tubes 42, and an outer sheath 46 of metal or other shielding material. Each metallic lamination 42, which, for example, may be of silver, copper, or aluminum, is connected at one end to one of a plurality of concentric annular rings 43 and is short circuited at the opposite end to a metallic disc 44 which is common to all of the metallic laminations. Connected in this manner, each two adjacent metallic laminations surrounds an individual magnetic lamination 45 and is the equivalent of a single thin sheet of conductor. All of the single conductors taken together comprise the first principal winding of the transformer.

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All of the individual magnetic laminations 45, which are preferably of a material having a high magnetic permeability and a low conductivity, taken together comprise the magnetic core of the transformer. The dimensions of each of the laminations may differ and are determined by the mode or modes desired to be applied to or removed from the transmission lines as will be discussed later. In order to best present the principles of the transformer, the laminations are shown as being of equal length and thickness in the included drawings. The laminations 45 are separated from their adjacent transformer elements by a dielectric material 47, and, in addition, the dielectric 47 separates the central rod 41 from the adjacent metallic lamination 42 and the disc 44, and also separates the sheath 46 from its adjacent metallic lamination. The annular metallic rings 43 are separated from each other and are arranged coaxially with respect to the longitudinal axis of the transformer and the transmission line so that contact is made between each ring and plurality of conducting laminations in the transmission line 30. Appropriate signal sources or signal utilization devices are provided for connection to the transformer depending on whether the transformer is used as a wave input means or a wave output means. A perspective view of the structure of transformer 32 in accordance with the above description is shown in Fig. 3.

Fig. 4 shows the input transformer 32 of Fig. 2 in accordance with the invention including both principal windings, and connections to signal sources to excite electromagnetic waves of the fundamental and higher order modes. Signal sources 51, 52 and 53 are connected respectively to the individual transformer windings 48, 49 and 50 which comprise the second principal windings of the transformer. Each of the individual windings enclose the magnetic laminations 45 in a manner so as to severally induce into the first winding of the transformer currents of density patterns appropriate to electromagnetic waves of the fundamental, second order and third order modes respectively. By way of illustration, winding 48 encloses all of the magnetic laminations in a single loop and the current flowing therethrough from source 51 in the direction indicated by the arrow in the drawing generates in the laminations 45 lines of magnetic flux concentric with the axis of the transformer and having the same polarity or direction. This flux in turn causes current to flow in the metallic laminations 42 which establishes therein the approximate current density pattern of the electromagnetic wave of the fundamental mode as shown in Fig. 1A. Additionally, winding 49 encloses that half of the total number of laminations near the axis of the transformer in one loop and the remaining magnetic laminations in a second loop so as to comprise, in effect, two individual windings connected in series opposition. Current flowing through the winding 49 from source 52 in the direction indicated by the arrow generates in the laminations 45 lines of flux which are concentric but which have directions which are opposite, respectively, in the outer laminations and the inner laminations. This flux pattern induces into the first winding a current density pattern similar to that of the electromagnetic wave of the second order mode as shown in Fig. 1B. By a similar process there is induced into the first winding a current density pattern similar to that of the electromagnetic wave of the third order as shown in Fig. 1C by source 53 and winding 50 which winding encloses the third of the total number of magnetic laminations near the axis of the transformer in one loop, the middle third in the second loop, and the remaining third in the third loop comprising in effect three individual windings connected in series such that the middle third is in opposition to the other two groups. These individual current density patterns may then be transmitted to the conductive laminations of the transmission line 30 by the rings 43, thereby launching in the transmission line simultaneously and

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independently signal bearing electromagnetic waves of the fundamental, second order and third order modes. It is understood, of course, that any one of these modes may be launched into the transmission line by itself. It will be noted that the individual second windings described above and as further shown in the enlarged view of Fig. 5 are arranged to cancel out the effect that the other windings might have on any one individual winding, so that substantially none of the fundamental mode signal appears in the second windings 49 and 50, substantially none of the second order mode signal appears in windings 48 and 50 and substantially none of the third order mode signal appears in windings 48 and 49. It will be obvious to one skilled in the art, in view of the circuitry of windings 48, 49 and 50, that additional sources and second windings can be connected to the transformer to provide for the application electromagnetic waves of higher order modes and that by an appropriate selection of second windings that any one or any combination of several modes can be applied to the transmission line at one time.

As the structure and the principle of operation of both transformers used in accordance with the invention as wave input means and wave output means are identical, it is clear that the wave transformer 32 of Fig. 4 may also be adapted for use as a wave output transformer by connecting individual current utilization devices respectively to the second windings 48, 49 and 50, in place of the signal sources 51, 52 and 53. Such utilization devices will remove substantially only that signal associated with the mode particular to the individual second winding to which it is connected.

In the laminations 45 comprising the core of the transformer the permeability and quantity of magnetic material is chosen so that only a small fraction of the current available is used to excite the core and the remainder of the current is available for useful output. In addition, it is necessary that the magnetic material be distributed between the individual laminations comprising the core so as to induce into each of the single thin sheet conductors surrounding each lamination currents which when viewed in all of the conductors connected to the annular rings 43 appear as a current density pattern or patterns similar to that of the mode or modes desired to be applied. This distribution may be effected by choosing individual laminations of given axial lengths or thickness or both. A core distributed in this manner in an output transformer will cause the individual mode appearing in its respective individual second winding to be substantially decoupled from the other modes in the line and any residual coupling between modes may be removed by any of the well known external decoupling systems such as a crosstalk balancing arrangement employing transformers commonly used with multiple transmission cables.

The number of turns for each individual second winding is determined from power considerations as in common simple transformers. For a given load impedance it is desirable that the number of windings be such that the power of an incident wave from the transmission line is absorbed without reflection and is delivered to the load.

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The invention has many advantages. Not only is the transformer simple and compact and suitable for use in applying electromagnetic waves of any mode to a laminated transmission line and removing such waves therefrom, but it is also useful in applying to and removing from such a laminated structure, independently and simultaneously, a plurality of electromagnetic waves of a variety of natural modes.

It is obvious that the invention is not restricted to the specific arrangements shown. For example, it is possible for a transformer in accordance with the invention to be combined in a single unit with a laminated transmission line of the Clogston type in which the magnetic laminations of the transformer would be made small and replace sections of the insulating laminations in the transmission line and the conductive laminations of the transformer would be made continuous with the conductive laminations of the transmission line. Other similar modifications and improvements can be made in the embodiments described above without departing from the scope of the invention.

What is claimed is:

1. A transformer comprising a plurality of spaced coaxial cores of magnetic material, a first winding comprising a plurality of single sheets of conductive material, each of said cores being enclosed by one of said sheets, and a plurality of second windings, each of said second windings enclosing a fraction of the total number of said cores in one loop and other fractions in other loops.
2. A transformer comprising a plurality of spaced coaxial cores of magnetic material, a first winding comprising a plurality of single sheets of conductive material, each of said cores being enclosed by one of said sheets, means for connecting said sheets to one another, a second winding enclosing all of said cores in one loop, and additional second windings each enclosing all of said cores, each said additional winding enclosing fractions of the total number of said cores in separate loops.
3. In combination, a transmission line and a transformer, said transmission line comprising a plurality of coaxially arranged cylindrical composite conductors and said transformer comprising a plurality of coaxially arranged tubular magnetic cores, a plurality of sheets of conductive material, each of said sheets enclosing one of said cores, means for connecting said sheets to the conductors of said transmission line, means for connecting said conductive sheets together, and a plurality of individual windings of a conductive material arranged with respect to said cores whereby an electric current flowing through each of said individual windings generates lines of magnetic flux in said cores characteristic of an electromagnetic wave desired to be propagated in said transmission line.

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