

Feb. 3, 1959

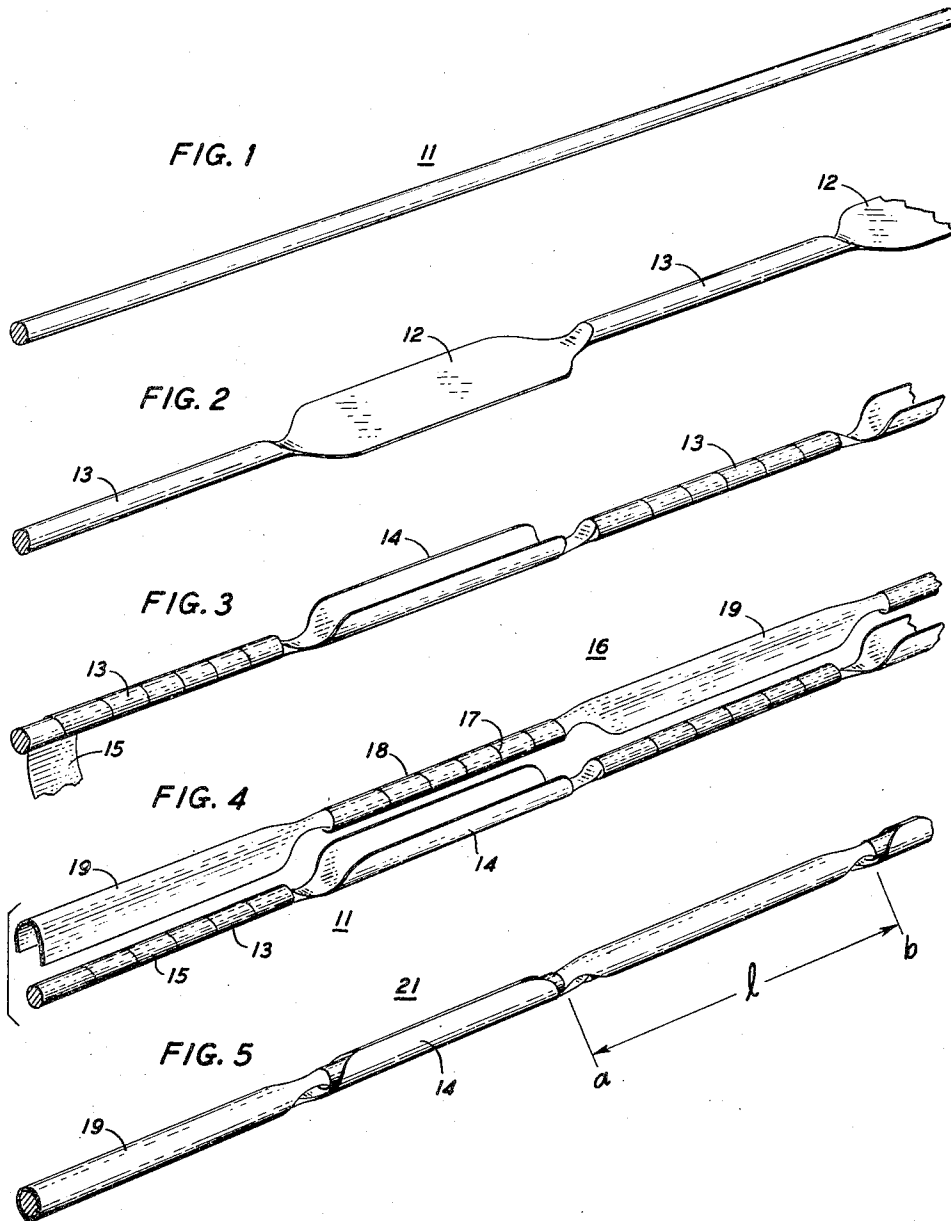
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2,872,501

CONDUCTOR HAVING TRANSPOSITIONS

Filed June 30, 1955

3 Sheets-Sheet 1



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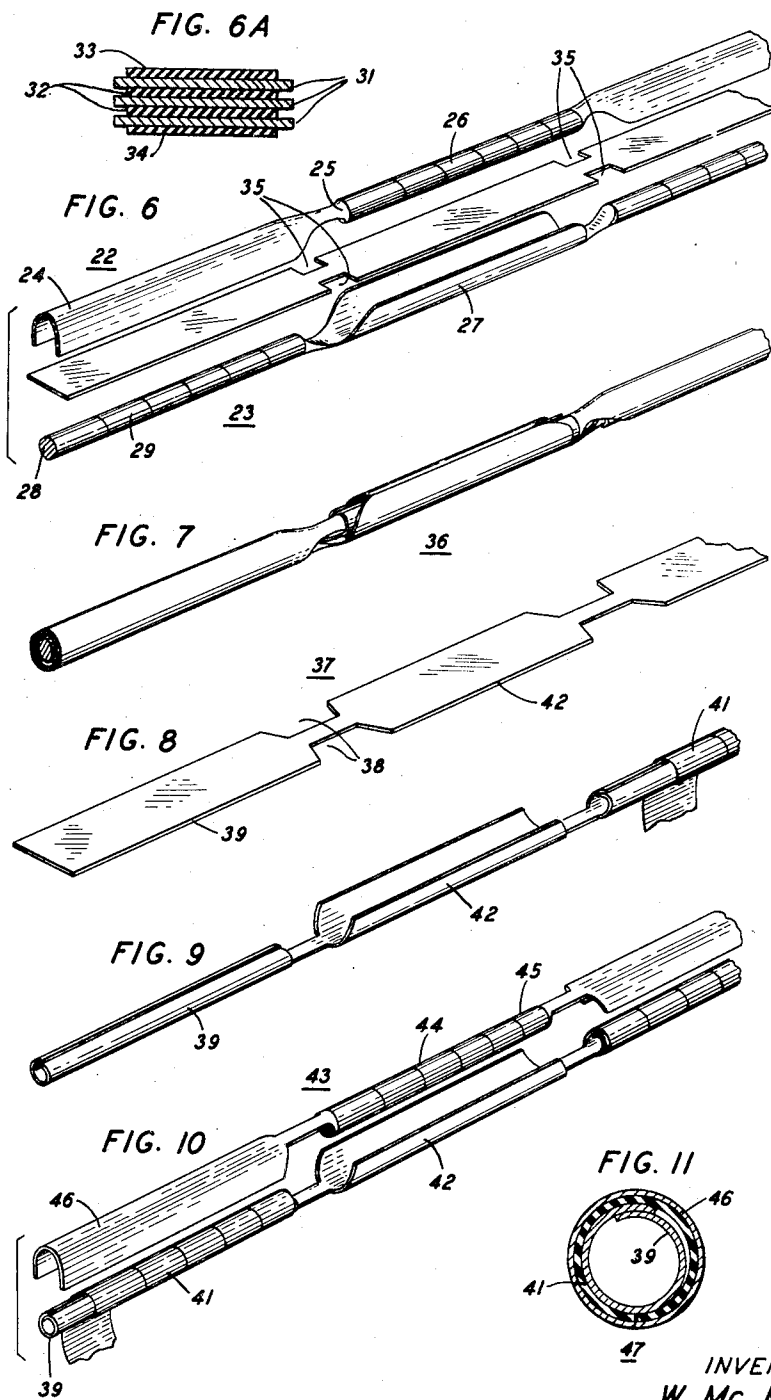
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3 Sheets-Sheet 2



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FIG. 12

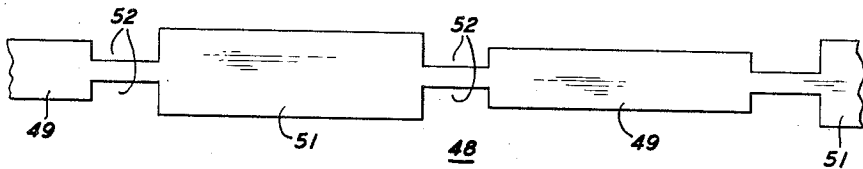


FIG. 13

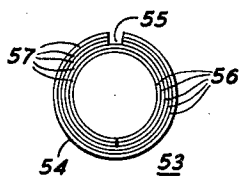


FIG. 14

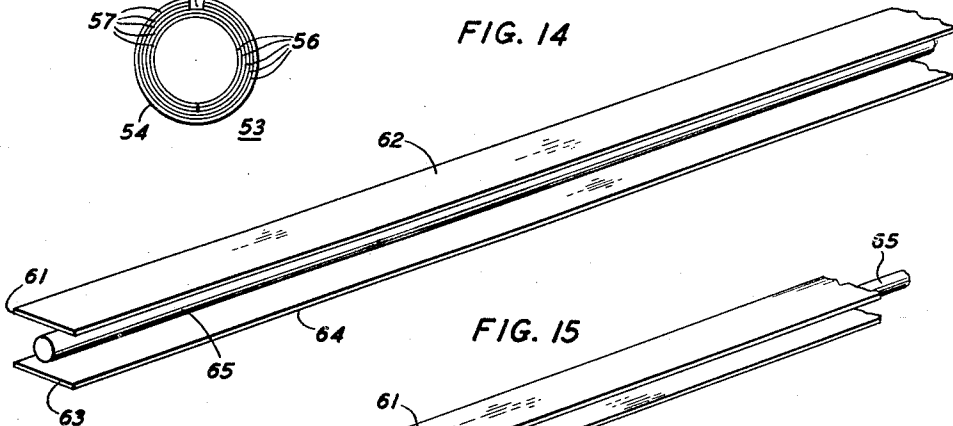


FIG. 15

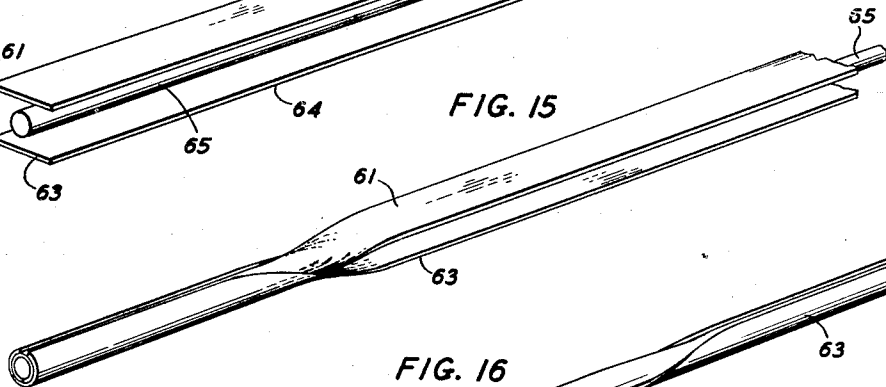


FIG. 16

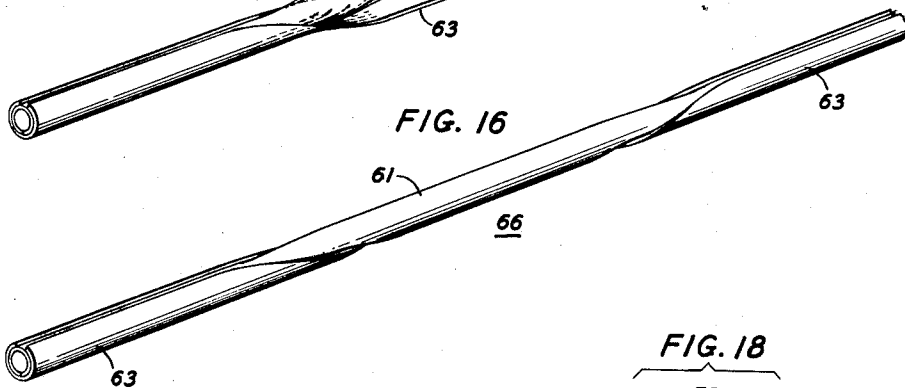


FIG. 17

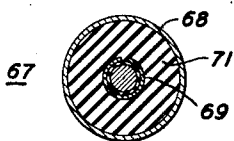


FIG. 18



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CONDUCTOR HAVING TRANSPOSITIONS

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4 Claims. (Cl. 174—34)

This invention relates to electrical conductors and more particularly to electrical conductors each comprising a plurality of transposed conducting elements and to methods of making them.

The term "transposed conducting elements" is used to refer to a plurality of conducting elements whose positions are shifted relative to each other and to an axis of the conductor. The shifting may be continuous along the length of the conductor or it may occur at discrete intervals. Also the transpositions may take the form of frequent shifting of large numbers of conducting strands as in the case of Litz wire, or it may be an orderly change of position of a few conductors such as, for example, the type shown and described in the United States patent application Serial No. 366,510 of W. H. Doherty which was filed July 7, 1953, now Patent No. 2,812,502, issued November 5, 1957.

It is an object of this invention to simplify the construction of electrical conductors having transpositions.

It is another object of this invention to provide an electrical conductor, the alternating-current resistance of which is less dependent upon frequency changes than that of conventional conductors.

In the transmission of electromagnetic waves, the current distribution which is substantially uniform throughout the cross-sectional area of the conductor at very low frequencies becomes nonuniform as frequency is increased. Consider, for example, the case of a solid conductor to which are applied waves of increasing frequency. At direct current and at very low alternating-current frequencies the current is substantially uniformly distributed throughout the cross-sectional area of the conductor and the resistance of the conductor and hence the conductor loss is at a minimum. As the frequency is increased, the current density becomes a maximum at that surface of the conductor which is exposed to the main field of the waves, which, in the present example, is the outer surface and decreases as distance from the field increases, i. e., toward the center of the conductor. The rate at which the current density decreases is dependent upon the frequency and the material of the conductor and, for most conducting materials, at high frequency the current density at the center of the conductor becomes negligible while the current density at the conductor surface is a maximum. This phenomenon is commonly known as skin effect and a skin depth is defined as the distance measured inwardly from the surface of the conductor in which the current in the conductor will decrease by one neper, i. e., the current density becomes

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

times the density at the surface of the conductor, where e is the natural logarithm base. Because of the skin effect phenomenon the alternating-current resistance of conductors increases as the frequency increases, becoming quite large at the higher frequencies, necessitating

frequent amplification of the signal along the transmission path.

It has long been recognized that alternating-current resistance of the conductor to high frequencies can be substantially reduced if the conductor is formed of a number of conducting elements or members connected in parallel and transposed often so that each element receives its share of exposure to the main field. This amounts to forcing the current to distribute itself over the entire cross-sectional area of the composite of individual conducting elements, thereby increasing the total current carrying area. It follows then that the alternating-current resistance is decreased substantially, and the frequency dependency of the alternating-current resistance is likewise decreased.

One well known example of a composite conductor which utilizes the foregoing principles is Litz wire which, while effective at lower frequencies, suffers from many disadvantages at the higher frequencies in that, first, each individual strand of wire must be insulated from all of the others, requiring great care of fabrication especially for operation at the higher frequencies; second, for effectiveness at the higher frequencies the diameter of the individual strands of wire must be made so small that of necessity there are great sacrifices in strength and ruggedness; third, with the large number of individual strands involved, proper transposition is exceedingly difficult to achieve especially when use at high frequencies is contemplated which requires numerous transpositions at very short intervals.

In accordance with the present invention, an electrical conductor having transposed conducting elements is provided which is a great improvement in many respects over other known transposed conductors. In an illustrative embodiment of the invention, flat sections are formed at periodically recurring intervals along a conducting wire by rolling or passing, the flat sections being slightly shorter in length than the sections of wire separating them. The flat sections are then formed into channels. A second wire is formed in the same way and the round sections of both wires are then coated with insulation. The round sections of each wire are then placed in the channels of the other wire and the channels are formed into hollow cylinders which surround the round sections of wire. As a result the two wires form a single composite conductor which has periodic transposition of the conducting elements along its length.

The invention will be more readily understood by referring to the following description taken in conjunction with the accompanying drawings in which:

Fig. 1 is a perspective view of a single wire from which one of the conducting elements of the conductor is made;

Fig. 2 is a perspective view of the wire of Fig. 1 after the initial forming step of one of the methods of the present invention has been performed;

Fig. 3 is a perspective view of the wire of Figs. 1 and 2 after the second step in the forming operation has been performed;

Fig. 4 is a perspective view of the two wires or conducting elements as they appear prior to the final step in the method of the present invention;

Fig. 5 is a perspective view of the finished electrical conductor having transposed conducting elements;

Fig. 6 is a perspective view of an intermediate step in the formation of a modification of the conductor of Fig. 5;

Fig. 6A is a cross-sectional view of one of the elements of the conductor of Fig. 6;

Fig. 7 is a perspective view of the modified conductor being formed in the step shown in Fig. 6;

Fig. 8 is a perspective view of a flat member from

which another embodiment of a transposed conductor is made;

Fig. 9 is a view of the member of Fig. 8 after the initial forming step has been made;

Fig. 10 is a view of the next to last step in the forming operation of the particular embodiment of transposed conductor;

Fig. 11 is a cross-sectional view of the completed embodiment of transposed conductor;

Fig. 12 is a plan view of a flat member similar to that shown in Fig. 8 for making a modified form of the conductor of Fig. 11;

Fig. 13 is a cross-sectional view of still another embodiment of the present invention;

Fig. 14 is a perspective view of the first step in the formation of still another embodiment of the transposed conductor of the present invention;

Fig. 15 shows an intermediate step in the formation of the conductor;

Fig. 16 is a view of the completed transposed conductor being formed in Figs. 13 and 14;

Fig. 17 is a cross-sectional view of a coaxial cable utilizing any one of the several embodiments of the present invention as the center conductor; and

Fig. 18 is a cross-sectional view of a parallel pair transmission line using the conductors of the present invention.

Turning now to Fig. 1, there is shown a round wire of conducting material such as, for example, copper. While the wire 11 as shown in Fig. 1 is round, it will be apparent from the following that it is not necessary that the wire have this particular configuration and applicant does not intend to restrict his invention solely to round wires, other cross-sectional configurations being adaptable to the method of the present invention. Wire 11 is then subjected to a forming operation wherein a plurality of flat sections 12 of uniform length, width and thickness are formed at intervals along the wire as best seen in Fig. 2. Flat sections 12 are equally spaced from each other along the length of wire by round sections 13, flat sections 12 being slightly shorter in length than sections 13. The forming operation may be performed in any suitable manner such as, for example, placing the wire 11 on a hardened steel plate and passing the plate and wire through a rolling mill, the setting of the mill determining the thickness and width of the flat sections and the length of the plate governing the length of the flat sections. It is obvious that other pressing or rolling operations will serve equally as well, the method here discussed being merely by way of example.

In Fig. 3 is shown the next step in the formation of the conductor of the present invention wherein the flat sections 12 of the wire of Fig. 2 are formed into channels 14. The formation of the channels 14 may be done by any suitable method such as, for example, a simple forming die. After the formation of the channels 14, the round sections 13 of the wire are then covered by suitable insulating material. In Fig. 3 the insulating material 15 is shown as a spiral wrapping of insulating tape. Obviously the insulation may be applied in other ways and may consist of any suitable insulating material. Thus the insulating material 15 may be sprayed onto the round sections 13 or it may be a lacquer or varnish coated or deposited on the wire 11 prior to any forming operations. In the latter case, it is obvious that such a coating must be tough and adhesive in order to withstand the subsequent forming operations.

In Fig. 4 there is shown the next step in the method of the present invention. A second conducting element 16 which has been operated upon in the same manner as the conducting element of 11 in Figs. 1, 2 and 3 and which has round section 17 coated with insulating material 18 and channel sections 19 formed therein is placed adjacent conducting element 11 so that the round sections 17 of conducting element 16 rest in the channels

14 of conducting element 11 and the round sections 13 of conducting element 11 rest in the channels 19 of conducting element 16. After conducting elements 11 and 16 have been assembled as shown in Fig. 4, the channels 14 and 19 are then formed into hollow cylinders which surround the circular sections 17 and 13, respectively, as best seen in Fig. 5, forming a complete conductor 21. The forming of the hollow cylinders can best be performed by suitable forming dies; however, any suitable forming means may be used to achieve the structure shown in Fig. 5.

It is readily apparent from a study of Fig. 5 that the structure there shown comprises a single conductor 21 having two conducting members which are periodically transposed so that they share equally exposure to the main field.

The effectiveness of transposition of conducting elements in a conductor depends to a considerable extent upon a judicious selection of the transposition interval, that is, the distance l between the points a and b in Fig. 5. It is desirable to transpose often enough to insure a substantial reduction in losses, yet, on the other hand, in the interests of ease and low cost of fabrication, it is desirable that the conducting elements be transposed no more frequently than is necessary. As long as the currents carried by the conducting elements are approximately equal, losses will be minimized, hence it is necessary to transpose only often enough to maintain this condition of approximate equality of currents in the conducting elements. In the drawings of the present invention, the particular embodiments shown are neither to scale nor proportion, inasmuch as the transposition interval may be quite long as compared to the length of the conductor over which the transposition is accomplished.

In Fig. 6 there is shown an intermediate step in the formation of a modified form of the conductor of Fig. 5. Two conducting members 22 and 23 are formed in the manner shown in Figs. 1, 2, and 3, conducting element 22 having sections 24 formed into channels and round sections 25 covered by suitable insulating material 26, and conducting element 23 having channel sections 27 and round sections 28 covered with insulating material 29. A plurality of thin, flat conducting sheets 31, separated by thin layers of insulating material 32 are formed into an elongated "sandwich," an enlarged cross section of which is shown in Fig. 6A, and interposed between conducting elements 22 and 23, as best seen in Fig. 6. Sheets 31 may be of any suitable conducting material, such as copper or aluminum foil, and insulating material 32 may be of any suitable material of low dielectric constant such as polystyrene. The insulating layers 32 and conducting layers 31 are preferably bonded together to form a unitary structure which is then coated with thin insulating layers 33 and 34. In the particular embodiment here shown, three conducting sheets are used. It is obvious that a greater or lesser number of sheets may be used, and applicant does not intend to limit himself to the particular number here shown. In order to facilitate final assembly, the "sandwich" may be notched or recessed as shown at points 35 in Fig. 6, although such notches are not necessary so long as the assembled "sandwich" is sufficiently flexible to permit the formation of the composite conductor 36 of Fig. 7. It can readily be seen that conductor 36 is quite similar to conductor 21 of Fig. 5, with the addition of conducting layers 31, the outer and inner ones of which are periodically transposed, as are the conducting elements 22 and 23. The conductor 21 of Fig. 5 and 36 of Fig. 7, by virtue of their transposed conducting elements, have a greatly reduced alternating-current resistance, the alternating-current resistance, furthermore, being much less frequency dependent.

While the particular embodiments thus far disclosed have utilized solid conducting wires having flat sections formed periodically along their length as the conducting

elements of the transposed conductor, it is possible to utilize flat conducting sheets as the conducting elements. In Fig. 8 there is shown a flat, elongated sheet 37 of conducting material having oppositely disposed pairs of notches 38 formed periodically along its length. The shape of the notches 38 is not critical, their purpose being to facilitate the subsequent forming operations. In Fig. 9 there is shown an intermediate step in the forming operation, wherein alternate sections 39 of member 37 which are formed by the notches 38 are rolled into cylindrical form. In Fig. 9 the edges of the cylinder are shown overlapping. As will be apparent hereinafter, this overlap is designed to permit a compact structure; however, it is not necessary that the edges overlap. They may abut or actually fail to touch without impairing to any serious extent the operation or performance of the transposed conductor. After the sections 39 are formed into cylindrical shape, they are covered with suitable insulating material 41 which is shown here as insulating tape wound around the sections 39. It is obvious that any suitable method of covering the sections 39 with insulating material may be used. Thus any of the ways of applying insulation as discussed with relation to Figs. 1 through 5 may be used, or any other suitable method.

As was the case in the formation of the conductors shown in Figs. 5 and 7, the remaining flat sections 42 of conducting member 37 are shaped in the form of channels, as shown in Fig. 10. A second conducting member 43 having cylindrical sections 44 covered with insulating material 45 and channel sections 46 is placed adjacent conducting member 37 as shown in Fig. 10 so that cylindrical sections 39 lie in channel sections 46 and sections 44 lie in sections 42. As was the case with the conductors of Figs. 5 and 7, the channel sections 42 and 46 are then closed around cylindrical sections 44 and 39, respectively, to form the completed conductor 47 having transposed conducting elements as shown in Fig. 11.

In Fig. 12 there is shown a modified form of conducting element 48 for making a transposed conductor substantially identical to conductor 47. Member 48, instead of having a plurality of sections of uniform width as was the case with member 37, has a plurality of alternating narrow sections 49 and wide sections 51 with notches 52 at the junctions of the sections. It will be readily apparent that by using members 48 to make a conductor similar to that shown in Fig. 11, the edges of all sections may be made to abut instead of overlap or not meet. By the same token any degree of overlap or gap may be achieved, if such is desired, by properly proportioning the relative widths of the sections 49 and 51. While the structures of Figs. 8 through 12 have all been shown with conducting elements comprising single elongated sheets of conducting material, it will be readily apparent that the sheets may comprise a plurality of thin layers of conducting material separated by thin layers of insulating material if desired, and applicant does not intend to limit himself to the particular embodiments here shown. Thus there is shown in Fig. 13 a conductor 53 made in the manner of the conductor of Fig. 11, in which the conducting elements 54 and 55 each comprise a plurality of conducting members 56 separated by insulating material 57.

The various conductors thus far described have all been made by methods which include various forming operations. It is possible, however, to form a conductor having transposed conducting elements in accordance with the principles of the present invention without going through many of the forming operations. In Figs. 14, 15, and 16 there is shown such a conductor and the steps involved in fabricating it. In Fig. 14 there is shown a first conducting element 61, preferably made of flexible tape of conducting material and having a layer 62 of insulating material on one surface thereof, and a second member 63 having an insulating layer 64 thereon. Members 61 and 63 are placed on either side of and coexten-

sive with an elongated cylindrical core member 65. Core member 65 may be made of either insulating or conducting material and is primarily used to furnish strength and support for the members 61 and 63. Obviously if member 65 is of conducting material, it must be insulated from members 61 and 63, by any one of a number of suitable methods such as those discussed in the foregoing, or other methods well known in the art. The next step in the formation of the conductor comprises wrapping members 61 and 63 around the core 65 in the manner shown in Fig. 15, so that one member is immediately adjacent the core and the other member surrounds it. At suitable intervals the positions of members 61 and 63 are reversed, as seen in Fig. 15, and, as a result, the completed conductor 66 as shown in Fig. 16 is formed. The particular method by which members 61 and 63 are reversed is not critical. If the members are formed of thin, flexible material, they may be transposed as shown, the slight distortion occurring at each crossing being too small to have any adverse effect in the performance of the transposed conductor. It will be obvious that instead of members 61 and 63 being coated with insulation, insulating material could be applied in the form of a tape or the like after wrapping one member about the core and before wrapping the other.

Thus far the disclosure has dealt with single conductors. In Figs. 17 and 18 are shown two possible applications of the conductor of the present invention. In Fig. 17 there is shown a coaxial cable 67 having an outer conductor 68, an inner conductor 69 which may take any one of the forms of conductors of the present invention, and dielectric material 71 which may be solid or gaseous material as is well known in the art. In Fig. 18 there is shown a parallel pair transmission line 72 having two conductors 73 and 74 which may be any of the several embodiments of the invention thus far discussed.

In all of the embodiments herein shown, the use of insulating material surrounding the composite conductor, or the use of metallic sheathing, is permissible. There has been no showing of such inasmuch as such practices are well known in the art and have, therefore, been omitted for the sake of clarity.

It is to be understood that the above-described arrangements are merely illustrative of the application of the principles of the invention, and applicant does not intend to limit his invention to the particular embodiments herein shown. Numerous other embodiments may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. The method of making a low loss electrical conductor which comprises forming a plurality of flat sections on a first length of wire and a second length of wire so that the flat sections so formed are separated from each other by sections of wire of approximately the same length as said flat sections, covering the sections of wire with insulating material, forming said flat sections into channels, inserting the sections of wire of the first wire into the channels of the second wire and the sections of wire of the second wire into the channels of the first wire, and forming the channels of the first and second wires into hollow sections which substantially enclose the sections of wire therein.

2. A low loss electrical conductor comprising two elongated continuous members of conducting material, each member being built up of solid cylindrical portions and channel portions alternately along the length thereof, said channel portions being sufficiently large to include the cylindrical portions, said members having their axes coincident with the solid cylindrical portions of each lying in the channel portion of the other and said channel portions being formed into hollow cylinders substantially surrounding said solid cylindrical portions of the other member, and means for insulating said members from each other.

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3. A low loss electrical conductor built up of two elongated continuous members of conducting material, each of said members having a series of alternate flat portions and solid portions of circular cross section, the axes of the members being coincident and the flat portions of each member being formed around the solid portions of the other member to substantially enclose the solid portion, and means for insulating the members from each other.

4. A low loss electrical conductor built up of two elongated continuous members of conducting material, each of said members having a series of alternate flat portions

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and portions of circular cross section, the axes of the members being coincident and the flat portions of each member being formed around the portions of circular cross section of the other member to substantially enclose the last-mentioned portions, and means for insulating the members from each other.

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