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COAXIAL CIRCUIT WITH STRANDED INNER CONDUCTOR

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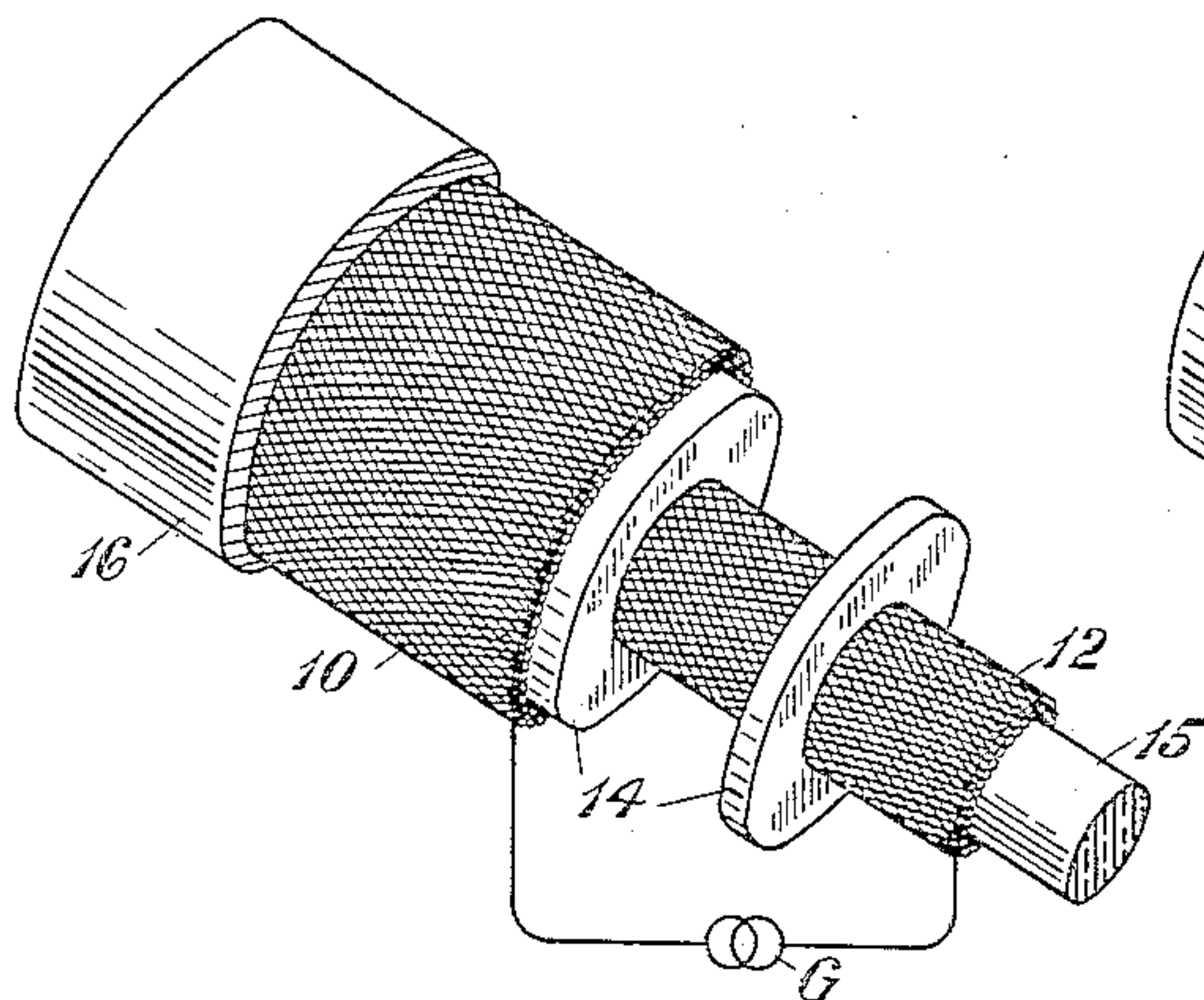


Fig. 1

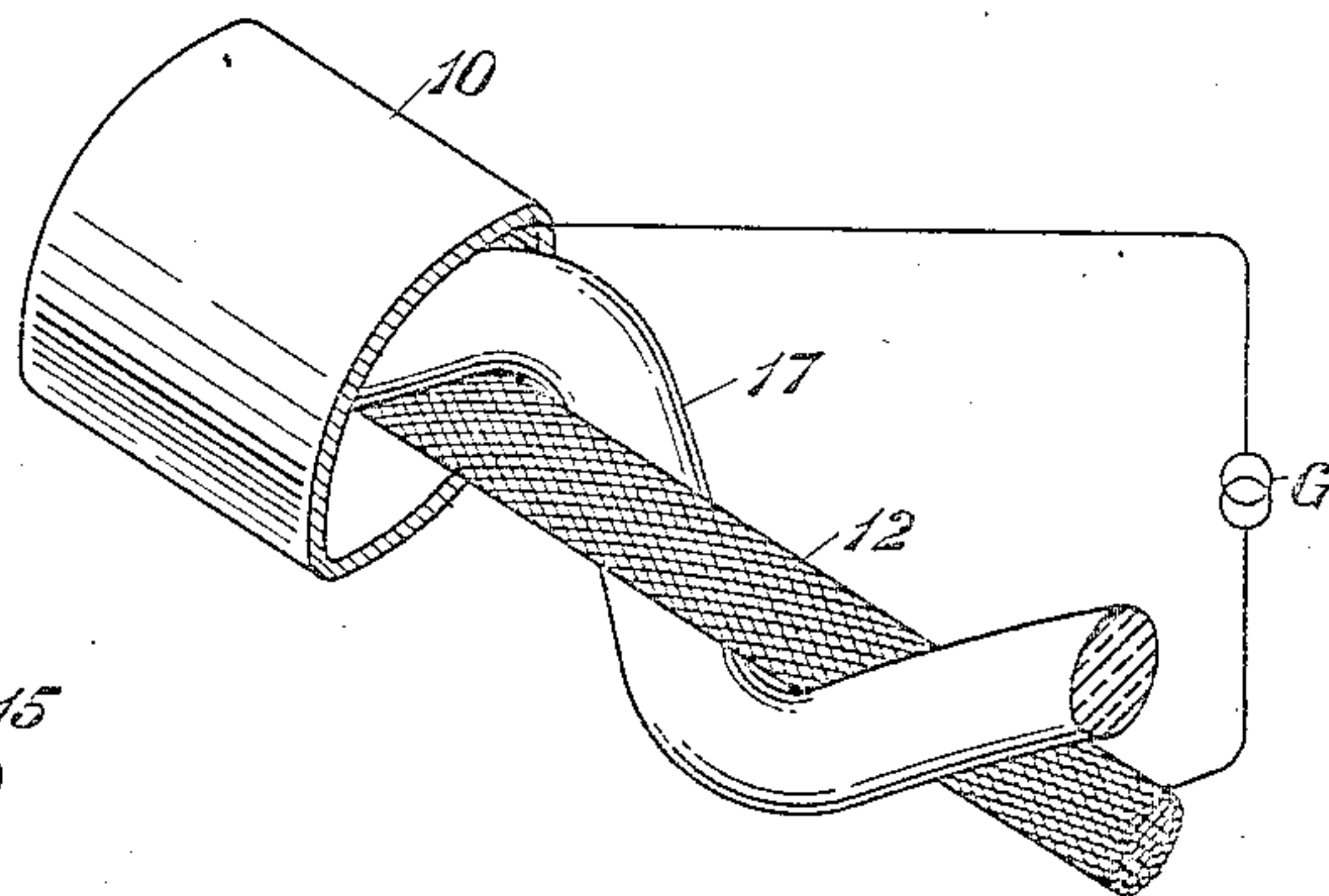


Fig. 2

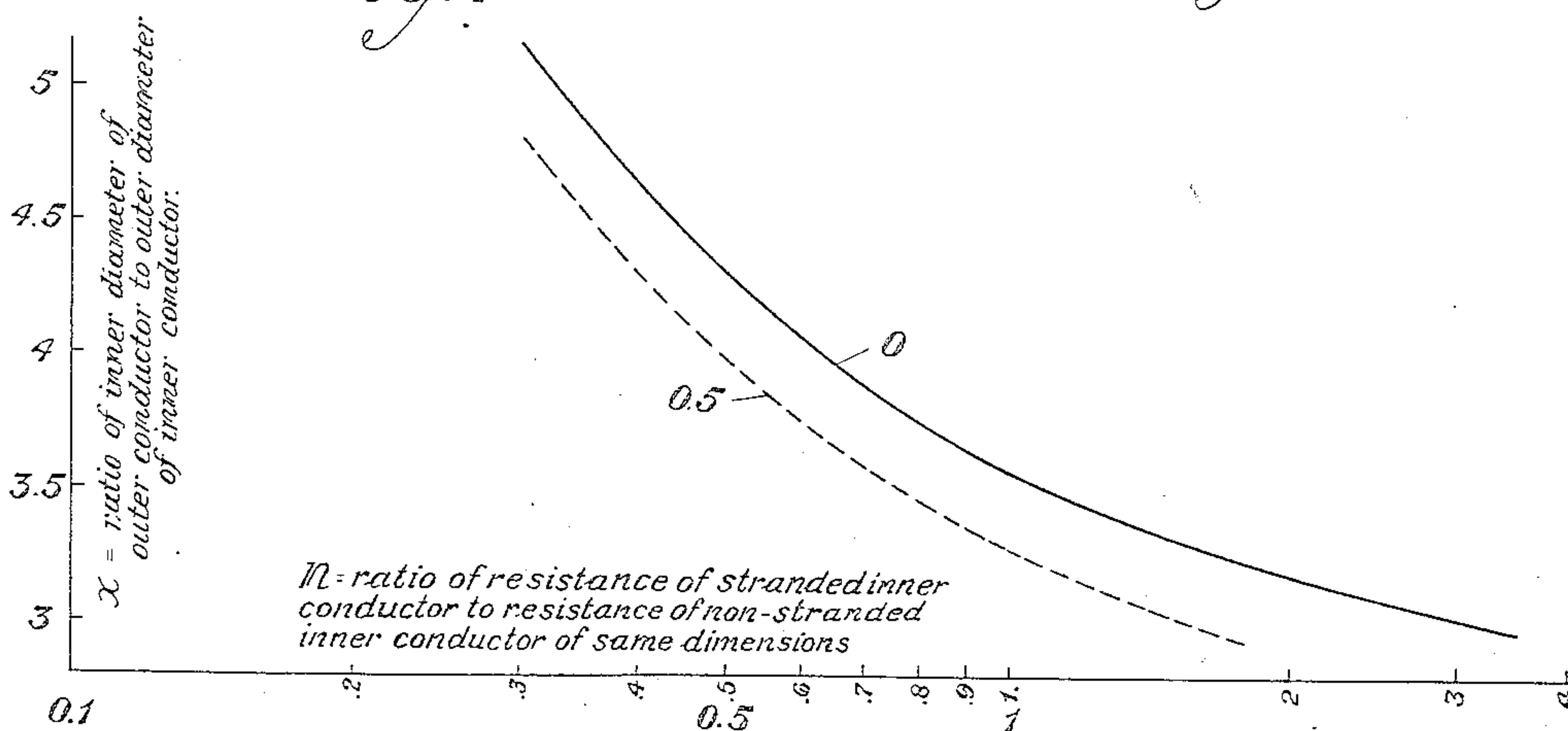


Fig. 3

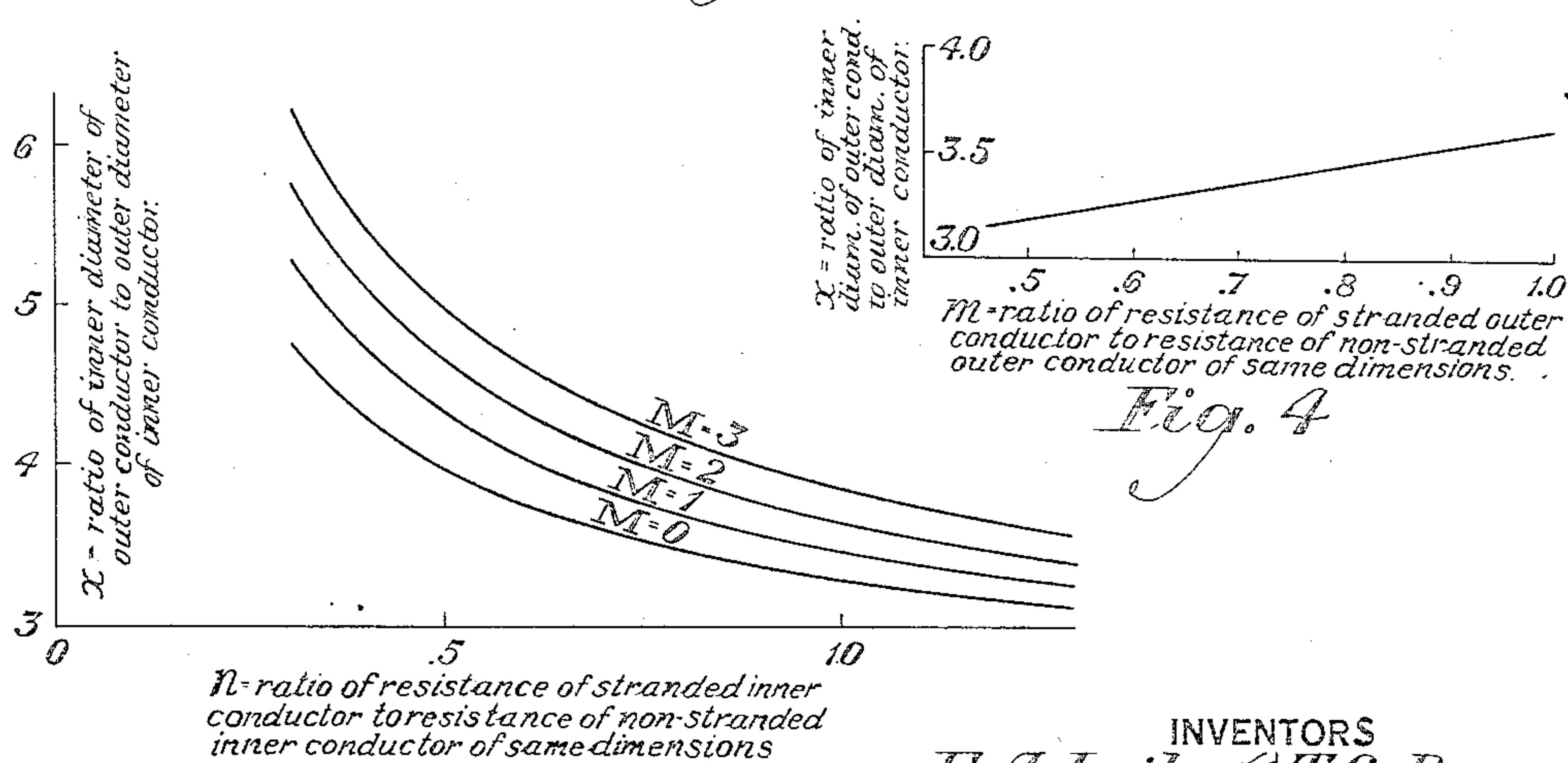


Fig. 4

$N = \text{ratio of resistance of stranded inner conductor to resistance of non-stranded inner conductor of same dimensions}$

Fig. 5

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COAXIAL CIRCUIT WITH STRANDED INNER CONDUCTOR

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This invention relates to a conducting system for transmitting with small attenuation a band of frequencies extending upwards to hundreds or thousands of kilocycles. In particular it deals with conductors which are arranged concentrically, one or both of the conductors consisting of a number of separately insulated strands.

Modern developments in the art of communication render it desirable to have available means for transmitting extremely wide bands of frequencies. On a system for telephone communication over long distances the cost of the line circuit is a large portion of the total cost, and any means which utilizes the line circuit more efficiently results in considerable saving. One method which has already been applied for this purpose is the use of multiplex or carrier transmission, whereby several conversations are transmitted simultaneously over one pair of line conductors. It would be desirable to greatly increase the number of talking channels on one pair of line conductors, but this requires the use of correspondingly higher frequencies for which ordinary types of circuits are not suitable on account of crosstalk, attenuation, and noise. From this standpoint, therefore, it is desirable to have available a circuit which will transmit extremely wide bands of frequencies without undue values of attenuation and interference.

Another factor is introduced by the modern development of television. The transmission of a well-defined representation of some large scene such as a sporting event or theatrical performance would require a band of frequencies extending from 0 to about 1000 kilocycles or higher, a range far beyond that which can be handled by the ordinary types of circuits.

In accordance with the present invention a circuit having these desirable wide band characteristics is obtained by employing concentric conductors, one acting as a return for the other. The two conductors may be insulated from each other and held in proper concentric relation by means of suitable insulating material arranged in any desired manner. This insulating material should preferably be of some dielectric having small power factor and low dielectric constant so as to reduce as far as possible the leakage loss between the conductors. To further minimize the leakage loss, it would be desirable to arrange the insulating material so that it occupies a small portion of the space between the outer and the inner conductors, the remainder of the space being filled with dry air or gas, which, as is well known, involves substantially no leakage loss. This could be accomplished, for example, by forming the insulating material in the shape of washers spaced as far apart as possible consistent with mechanical support, or by making it in the form of a spiral strand or helix with a

large pitch. In the case of a flexible conductor which would be subjected to considerable bending it might be necessary, however, to fill the entire space with insulation. The conductors might consist of tubing made of any suitable conductive material such as copper, and in the case of the inner conductor a solid wire may be substituted for the tube if desired.

In such a conducting system, the resistance of the conductors increases with frequency due to the well-known skin effect, which causes the current to crowd to the outer surface of the inner conductor and to the inner surface of the outer conductor, thereby increasing the conductor resistances. In a well designed system, at high frequencies, a large part of the attenuation is due to the resistance of the conductors, and it would thus be desirable to reduce their resistance. This can be accomplished by making each conductor of a number of individually insulated strands so interwoven or twisted that each strand passes alternately back and forth from the surface of the conductor. An arrangement of this type causes the current to be more nearly uniformly distributed throughout the cross-section of the conductor, and the A. C. resistance is thereby reduced due to the more effective use of the conducting material, as set forth in the patent to Affel and Green, No. 1,818,027, dated August 11, 1931.

A conducting system such as that outlined above has a number of advantages. It may be made waterproof by the application of a protecting sheath, with the result that the leakage losses between the conductors (which in the case of ordinary open-wire construction vary greatly with weather conditions and at high frequencies contribute very substantially to the attenuation) may be made small and constant. Also, the form of construction is such that interference to or from nearby circuits, and noise coming from external sources can be made practically negligible. The attenuation may be made very small by increasing the conductor dimensions, consistent with practical problems of construction and installation. In any case, the attenuation at high frequencies may readily be made much smaller than the attenuation of open-wire or cable circuits, thus making possible the commercial transmission of wide bands of frequencies over long distances. When distances of the order of hundreds or thousands of miles are to be spanned, it will of course be necessary to make use of amplifiers spaced at suitable intervals as is done in the case of existing signal transmission circuits.

A particular object of the invention is to proportion such a coaxial circuit (with one or both conductors composed of insulated strands) in

such a manner as to obtain minimum high frequency attenuation.

The invention will now be more fully understood from the following description when read in connection with the accompanying drawing, of which Figure 1 is a perspective view in partial section of a portion of the conducting system in accordance with the present invention, Fig. 2 is a perspective view in partial section of a modified form of conductor system, and Figs. 3, 4 and 5 are curves illustrating certain characteristics of the concentric conductor systems which are described herein.

Referring to Fig. 1 of the drawing, 10 designates the outer conductor, 12 the inner conductor, 14 a plurality of dielectric washers for separating the two conductors, 15 a core upon which the inner conductor is mounted, and 16 a waterproof covering for encasing the entire construction. One of the conductors acts as a return for the other and not as a mere shield, this fact being indicated by the conventional representation of a source of alternating electromotive force G with its terminals connected to the two conductors. The inner conductor is formed by braiding a number of separately insulated strands of copper or other conductive material over the core 15 to form in effect a tubular conductor. If desired, the strands might be arranged by a process similar to that used in the construction of rope, wherein a few strands are twisted together to form a group, a number of groups then being twisted together to form a larger group, and so on until a number of groups of the desired size are obtained, which may then be twisted around the core 15 to form a tubular conductor. Any other suitable method could be employed which would accomplish the object of causing each individual strand to pass alternately to and from the surface of the conductor so that it successively occupies all possible positions in the cross-section of the conductor, and at the same time does not lie constantly adjacent to very many other strands. Upon this conductor the spacing and insulating washers 14 are mounted.

The outer conductor is then formed by braiding a number of separately insulated strands of conductive material over the outer surfaces of the spacing washers to form in effect a conducting tube. Instead of braiding, any other suitable method of arranging the strands could be employed as previously described for the inner conductor. The waterproof covering which surrounds the outer conductor may be of any known type, such as will serve the dual purpose of mechanical protection and prevention of the entrance of water into the interior of the system. Since the shielding effect against external sources of interference obtained with a solid wall tubular outer conductor is to a considerable extent impaired when the outer conductor is composed of insulated strands, it might be desirable to have the waterproof covering made of conductive material which would act as a shield. Moreover, such a shield will prevent interference from the concentric conductor circuit into external circuits, thus effectively isolating the concentric conductor circuit electrically. In this case the waterproof covering would serve in addition as an electrical shield to the conducting system enclosed therein. Generally the thickness of shield which is necessary for mechanical reasons will afford sufficient electrical protection.

Fig. 2 of the drawing shows a modified form of conductor system, in which 10 designates the outer conductor, 12 the inner conductor, and 17 the insulating material which maintains the conductors in concentric relation. One of the conductors acts as a return for the other, as indicated by the conventional representation of a source of alternating electromotive force G with its terminals connected to the two conductors. The inner conductor 12 is formed of a number of separately insulated conducting strands suitably braided or interwoven so as to pass to and from the surface of the conductor and forming a cylindrical conductor whose cross-section is completely filled with said strands. Around the inner conductor is wrapped a strip 17 of any suitable insulating material, such as a paper or rubber string, said strip being applied in the form of a helix with a comparatively large pitch in order that the space between the inner and the outer conductors may consist principally of dry air or gas. This strip of insulating material serves to support the inner conductor concentrically within the outer conductor 10, which consists of a tube of conductive material, such as copper. In this case the outer conductor provides mechanical protection for the system, in addition to acting as a return for current flowing in the inner conductor and serving as an electrical shield for the system.

It is apparent that a coaxial conductor system of the type herein described may be made in many different forms, of which the construction shown in Figs. 1 and 2 are merely two examples. For instance, if it be desired to construct a coaxial system which shall be extremely flexible and which may be subjected to considerable handling, it might be necessary to completely fill the space between the two conductors with insulating material, such as rubber, in order to prevent the conductors from being forced in contact with one another by severe mechanical strains. In this case each of the two conductors could be made of a number of separately insulated strands of copper wire so interwoven or twisted that each strand successively occupies all possible positions in the cross-section of the conductor, and at the same time does not remain continuously adjacent to more than a few of the other strands comprising the conductor.

In any transmission system it is important that the attenuation at the maximum transmitted frequency be less than some critical value above which the usefulness of the system would be impaired. This critical value depends, of course, upon the particular case under consideration, and is determined by the amount of power available at the transmitting end of the system, by the amount of power which may be safely applied to the system, by conditions of crosstalk to and from adjacent systems, by interference due to external sources of power, by the available amount of amplification at the receiving end of the system, by the noise currents due to thermal agitation of electric charge in the conductors, by the amount of power necessary to operate the load which is connected to the receiving end of the system, and by similar and other limitations known to persons skilled in the art. With respect to a number of the above items, a concentric conductor system is superior to open-wire or cable circuits, and in particular it has such low values of crosstalk and interference that these factors are no limitation to its use at frequencies above the audible range. Furthermore, the at-

tenuation of a coaxial circuit may ordinarily be made as small as desirable by increasing the size of the conductors, consistent with practical limitations of construction and installation. It is important, however, that the dimensions of the inner and outer conductors be properly proportioned, as a mere increase in size may not result in the desired reduction of attenuation. Correct proportioning is likewise desirable as it permits the use of smaller conductors than would otherwise be necessary to secure a given attenuation, and thus leads to an economical design of a transmission system.

The method of proportioning a coaxial circuit in which either conductor or both conductors are composed of insulated strands, in order to secure minimum attenuation at high frequencies will not be considered.

At frequencies above the audible range, the attenuation of a transmission circuit is given by the formula:

$$A = \frac{R}{2} \sqrt{\frac{C}{L}} + \frac{G}{2} \sqrt{\frac{L}{C}} \quad (1)$$

R, L, G and C being respectively the resistance, inductance, leakance, and capacitance, all values in this and subsequent formulas being expressed in c. g. s. electromagnetic units. In a coaxial circuit, R is the resistance of the inner conductor plus the resistance of the outer conductor, L is the inductance of the dielectric plus the internal inductances of the two conductors, G and C are respectively the leakance and capacitance of the dielectric.

Let a be the inner radius of the inner conductor, b the outer radius of the inner conductor, c the inner radius of the outer conductor, d the outer radius of the outer conductor, f the frequency, λ the conductivity of the conductor material, ϵ the average dielectric constant of the dielectric, and p the average power factor of the dielectric. The inductance, capacitance and the leakance of the dielectric are given by the expressions:

$$L_d = 2 \log_e \frac{c}{b} \quad (2a)$$

$$C = \frac{\epsilon}{2 \log_e \frac{c}{b}} \quad (2b)$$

$$G_d = \frac{\pi f p \epsilon}{\log_e \frac{c}{b}} \quad (3)$$

When the inner conductor is completely stranded as illustrated in Fig. 2, its resistance can be computed by a formula given in an article by S. Butterworth, which is published in the Philosophical Transactions of the Royal Society of London, vol. 222, page 57. Equation (85) therein should be modified by the omission of the two terms involving D^2 , thus giving an expression for the resistance of a straight cylindrical conductor whose cross-section is completely filled with well transposed separately insulated strands.

When the inner conductor is stranded and of annular cross-section as illustrated in Fig. 1, its resistance must be determined by measurement, as no published formula appears to be available. Likewise for a stranded outer conductor, the resistance must be obtained by measurement.

The internal inductance of an inner conductor whose cross-section is completely filled with insulated strands is very nearly equal to 0.5 abhenry per centimeter at frequencies from zero up to very high values. This figure is the internal

inductance of a solid wire for direct current, being determined by the fact that the current density is uniform over the cross-section of the conductor. When a conductor is composed of suitably transposed insulated strands, uniform current distribution is maintained up to very high frequencies, and thus the internal inductance remains substantially the same as the D. C. value.

The internal inductance of a stranded conductor of annular cross-section likewise remains substantially constant from zero up to very high frequencies, and is very nearly equal to the D. C. internal inductance of a solid wall tube of the same dimensions. When used as the inner conductor of a coaxial circuit, the internal inductance is:

$$L_i = \frac{b^2 + a^2}{2(b^2 - a^2)} - \frac{2a^2}{b^2 - a^2} + \frac{2a^4}{(b^2 - a^2)^2} \log_e \frac{b}{a} \quad (4)$$

When used as the outer conductor of a coaxial circuit, the internal inductance is:

$$L_o = \frac{d^2 + c^2}{2(d^2 - c^2)} - \frac{2d^2}{d^2 - c^2} + \frac{2d^4}{(d^2 - c^2)^2} \log_e \frac{d}{c} \quad (5)$$

Since no general formula for the resistance of a stranded conductor is available, there will be introduced at this point two factors, n and m , applying to the inner and outer conductors respectively, these factors being defined as the ratio of the high frequency resistance of a conductor composed of insulated strands to the resistance at the same frequency of a non-stranded conductor of the same dimensions. Accordingly, at frequencies above the audible range, the resistance of a stranded inner conductor may be expressed by the formula:

$$R_i = \frac{n}{b} \sqrt{\frac{f}{\lambda}} \quad (6)$$

Similarly for the outer conductor:

$$R_o = \frac{m}{c} \sqrt{\frac{f}{\lambda}} \quad (7)$$

It will be appreciated that n and m may vary over a range of values which depends upon the frequency and upon the dimensions and configuration of the stranded conductors. However, at a given frequency and for a particular conductor, the value of n (or m) is definite and determinable. Since the attenuation of a coaxial conductor system of the type herein described in general increases with increase of frequency, and since the highest attenuation of a transmission system determines its degree of usefulness, it is desirable to so proportion the system that optimum relations are obtained at the highest frequency which is to be transmitted. Accordingly the variations of n or m with frequency need not be considered in deriving the relations for optimum proportions. Furthermore, n (or m) will not vary rapidly with changes in conductor dimensions, provided that the number of strands be changed as the conductor size is varied.

It, therefore, becomes possible to treat n and m as constants in deriving the relation for optimum proportions of a coaxial system. When the formulas so obtained are used for design purposes, it is, of course, necessary to bear in mind these conditions, and if a large range of sizes is involved it may be necessary to use the method of successive approximations if changes of n and m are of appreciable magnitude.

The attenuation of a coaxial conductor system in terms of its dimensions may be obtained by

combining formulas (1), (2), (2a), (3), (6) and (7):

$$A = \frac{1}{2} \left(\frac{n}{b} + \frac{m}{c} \right) \sqrt{\frac{f}{\lambda}} \sqrt{\frac{\epsilon}{4 \left(\log_e \frac{c}{b} \right)^2 + 2L' \log_e \frac{c}{b}}} \quad (8)$$

$$+ \pi f p \sqrt{\epsilon} \sqrt{1 + \frac{L'}{2 \log_e \frac{c}{b}}}$$

wherein L' is the sum of the internal inductances of the two conductors as given in the text or in formulas (4) and (5) according to the particular types of conductors under consideration.

Coaxial conductor systems may be divided into two classes: I, where the dielectric loss is so small as to be negligible; and II, where the dielectric loss is appreciable. Under each of these classes there will be considered three subdivisions: *a*, only the inner conductor is stranded; *b* only the outer conductor is stranded; and *c*, both conductors are stranded.

Ia. Dielectric loss negligible, only the inner conductor stranded. This case is of greatest importance for two reasons; first, by suitable choice and arrangement of the insulating material it is possible to reduce the dielectric losses to relatively small values, and second, since the greater part of the resistance of a coaxial system is due to the inner conductor, proportionately more reduction of the attenuation of the system can be obtained when the inner conductor is stranded. Under these conditions the attenuation may be expressed:

$$A = \frac{1}{2} \left(\frac{n}{b} + \frac{1}{c} \right) \sqrt{\frac{f}{\lambda}} \sqrt{\frac{\epsilon}{4 \left(\log_e \frac{c}{b} \right)^2 + 2L_i \log_e \frac{c}{b}}} \quad (9)$$

In this case, the sum of the internal inductances of the two conductors (L'), may be considered equal to the internal inductance of the inner conductor (L_i), as the internal inductance of a non-stranded conductor at high frequencies is so small as to be negligible.

Expressing the ratio of c to b as x , and setting the derivative of A with respect to x equal to zero, we obtain:

$$\frac{2nx \log_e x}{nx + 1} = \frac{4 \log_e x + L_i}{2 \log_e x + L_i} \quad (10)$$

This equation gives the relations which must exist between the ratio of the diameters of the two conductors, the internal inductance of the inner conductor, and the ratio of the resistance of the inner conductor to the resistance of a non-stranded conductor of the same dimensions, in order that the attenuation of a coaxial conductor system having a given size of outer conductor will be a minimum.

Fig. 3 shows a graph of Equation (10) for two values of L_i , the curve marked 0 being for the condition that $L_i = 0$, and the curve marked 0.5 being for the condition that $L_i = 0.5$ abhenry per centimeter. The latter curve applies to the case when the cross-section of the inner conductor is completely filled with insulated strands. When the inner conductor is of annular cross-section, the optimum value of the diameter ratio, (x), will lie somewhere between the two curves shown, approaching more closely to the curve marked 0 as the portion of the cross-section of the inner conductor occupied by strands is reduced. It has been found that the values of n which are obtained for conductors of reasonable dimen-

sions and sizes of strands lie above approximately 0.5, and since it is unlikely that values of n greater than unity will be advantageous in practice, the useful range of n may be taken as lying between these two figures. The corresponding range of diameter ratio (x) is from about 3.3 to 4.3.

In deriving the relations for minimum attenuation in this case, as well as in the subsequent cases, it has been assumed that the two conductors of the circuit are perfectly concentric. It should, of course, be appreciated that practical difficulties of construction prevent the realization of this condition, and that small values of eccentricity will be present. For moderately small departures from perfect concentricity, however, such as might be tolerated in practice, it can be shown that the conditions for minimum attenuation are substantially the same as in a circuit which has no eccentricity.

Ib. Dielectric loss negligible, only the outer conductor stranded. This case might apply when it is desired to obtain a mechanically flexible coaxial system. The attenuation of a conductor system of this type is:

$$A = \frac{1}{2} \left(\frac{x + m}{c} \right) \sqrt{\frac{f}{\lambda}} \sqrt{\frac{\epsilon}{4 (\log_e x)^2 + 2L_o \log_e x}} \quad (11)$$

The relations between x , m , and L_o which result in minimum attenuation are obtained by setting the derivative of A with respect to x equal to zero, which gives the equation:

$$\frac{2x \log_e x}{x + m} = \frac{4 \log_e x + L_o}{2 \log_e x + L_o} \quad (12)$$

It may be noted, however, that when the wall thickness of a stranded outer conductor is small compared with its diameter, its internal inductance is small compared with the dielectric inductance of the circuit. In this case the relations for minimum attenuation are very closely represented by:

$$x \log_e x = x + m \quad (13)$$

Fig. 4 is a graph of Equation (13), and shows the relation which exists between the ratio of the conductor diameters and the ratio of the resistance of a thin-walled stranded outer conductor to a non-stranded conductor of the same dimensions when the coaxial conductor system has minimum attenuation. Assuming that the useful range of m is from 0.5 to 1, (as is the case for n), and that the outer conductor wall thickness is small, it is seen that the optimum diameter ratio lies between approximately 3.2 and 3.6.

Ic. Dielectric loss negligible, both conductors stranded. The attenuation is:

$$A = \frac{1}{2} \left(\frac{nx + m}{c} \right) \sqrt{\frac{f}{\lambda}} \sqrt{\frac{\epsilon}{4 (\log_e x)^2 + 2L' \log_e x}} \quad (14)$$

and the condition for minimum attenuation:

$$\frac{2nx \log_e x}{nx + m} = \frac{4 \log_e x + L'}{2 \log_e x + L'} \quad (15)$$

As discussed under cases *Ia* and *Ib*, the values of n and m may lie in the range from about 0.5 to 1, and the value of L' may lie between approximately 0 and 0.5. The corresponding values of x are in the range from 2.9 to 4.3. If $n = m$, (a condition which might be approached in a practical system), the values of x are restricted to a much narrower range, lying between 3.3 and 3.6.

IIa. Dielectric loss appreciable, only the inner

conductor stranded. The attenuation of the system is:

$$A = \frac{1}{2} \left(\frac{nx+1}{c} \right) \sqrt{\frac{f}{\lambda}} \sqrt{\frac{\epsilon}{4 (\log_e x)^2 + 2L_i \log_e x}} + \pi f p \sqrt{\epsilon} \sqrt{1 + \frac{L_i}{2 \log_e x}} \quad (16)$$

and the condition for minimum attenuation:

$$2nx \log_e x - (nx+1) \frac{4 \log_e x + L_i}{2 \log_e x + L_i} - ML_i = 0 \quad (17)$$

where

$$M = 2\pi c p \sqrt{f \lambda}.$$

15 An idea of the magnitude of M and consequently its effect on the optimum diameter ratio can be obtained by noting that for a half-inch diameter coaxial system composed of copper conductors and having a dielectric of power factor $=0.01$, M is approximately equal to unity at a frequency of one megacycle. Fig. 5 shows the relations between n and x for several values of M , on the assumption that $L_i=0.5$, which, as previously described, applies to the case where the cross-section of the inner conductor is completely filled with insulated strands. Assuming that the useful range of n is from 0.5 to 1.0, and that M is not greater than 2.0, it will be seen that the optimum values of x lie between approximately 3.3 and 4.7.

Iib. Dielectric loss appreciable, only the outer conductor stranded. The attenuation is:

$$A = \frac{1}{2} \left(\frac{x+m}{c} \right) \sqrt{\frac{f}{\lambda}} \sqrt{\frac{\epsilon}{4 (\log_e x)^2 + 2L_o \log_e x}} + \pi f p \sqrt{\epsilon} \sqrt{1 + \frac{L_o}{2 \log_e x}} \quad (18)$$

and the condition for minimum attenuation:

$$2x \log_e x - (x+m) \frac{4 \log_e x + L_o}{2 \log_e x + L_o} - ML_o = 0 \quad (19)$$

As previously stated, the internal inductance of a thin-walled stranded outer conductor is small compared with the dielectric inductance of the coaxial system, and Equation (19) may be closely represented by Equation (13). Fig. 4, therefore, shows the approximate relations for minimum attenuation for a coaxial system having a thin-walled stranded outer conductor and having an appreciable value of dielectric loss. When m lies between 0.5 and 1, the optimum diameter ratio is between approximately 3.2 and 3.6.

Iic. Dielectric loss appreciable, both conductors stranded. The attenuation is given by Equation (8), and the condition for minimum attenuation is:

$$2nx \log_e x - (nx+m) \frac{4 \log_e x + L'}{2 \log_e x + L'} - ML' = 0 \quad (20)$$

60 When the values of n and m lie in the range from 0.5 to 1, the value of L' between 0 and 0.5, and the value of M less than 2, the corresponding values of x are between approximately 3.3 and 4.7. If $n=m$, the values of x are between approximately 3.3 and 4.1.

It will be obvious that the general principles herein disclosed may be embodied in many other organizations widely different from those illustrated without departing from the spirit of the invention as defined in the following claims.

What is claimed is:

1. A transmission circuit for transmitting frequencies well above the audible range comprising two substantially concentric conductors arranged one inside the other, said conductors being

insulated from one another and being connected one as a return for the other, at least one of said conductors being composed of a plurality of conducting strands insulated from one another so that the internal inductance of said conductor will be materially greater than zero and the ratio of the resistance of the stranded conductor to a non-stranded conductor of the same size will be substantially less than unity, the ratio of the inner diameter of the outer conductor to the outer diameter of the inner conductor being so related to the resistance ratio of stranded to non-stranded conductor and to the internal inductance of the conductor system that the attenuation of said circuit at a given high frequency transmitted over said circuit will be a minimum.

2. A transmission circuit comprising two substantially concentric conductors arranged one inside the other, said conductors being insulated from one another and being connected one as a return for the other, the outer conductor being composed of a plurality of conducting strands insulated from one another, said outer conductor being surrounded by a conducting shield, said circuit being substantially isolated electrically by said shield at frequencies above the audible range, the ratio of the inner diameter of said outer conductor to the outer diameter of the inner conductor being such that the attenuation of said circuit at a given high frequency will be a minimum.

3. A transmission circuit comprising two substantially concentric conductors arranged one inside the other and connected one as a return for the other, said conductors being insulated from one another by a substantially gaseous medium, at least one of said conductors being composed of a plurality of conducting strands insulated from one another, the ratio of the inner diameter of the outer conductor to the outer diameter of the inner conductor being such that the attenuation of said circuit at a given high frequency will be a minimum.

4. A transmission circuit for transmitting frequencies well above the audible range comprising two substantially concentric conductors arranged one inside the other, said conductors being insulated from one another and being connected one as a return for the other, at least one of said conductors being composed of a plurality of conducting strands insulated from one another so that the internal inductance of said conductor will be materially greater than zero and the ratio of the resistance of the stranded conductor to a non-stranded conductor of the same size will be substantially less than unity, the ratio of the inner diameter of the outer conductor to the outer diameter of the inner conductor being functions of the resistance ratio of stranded to non-stranded conductor and of the internal inductance of the conductor system, said diameter ratio having such a value between 3.2 and 4.7 as will produce minimum attenuation.

5. A transmission circuit for transmitting frequencies well above the audible range comprising two substantially concentric conductors arranged one inside the other, said conductors being insulated from one another and being connected one as a return for the other, the inner conductor being composed of a plurality of conducting strands insulated from one another so that the internal inductance of said conductor

will be materially greater than zero and the ratio of the resistance of the stranded conductor to a non-stranded conductor of the same size will be substantially less than unity, the ratio of the inner diameter of the outer conductor to the outer diameter of said inner conductor being functions of the resistance ratio of stranded to non-stranded conductor and of the internal inductance of the conductor system, said diameter ratio having such a value between 3.3 and 4.7 as will produce minimum attenuation.

6. A transmission circuit for transmitting frequencies well above the audible range comprising two substantially concentric conductors arranged one inside the other, said conductors being insulated from one another and being connected one as a return for the other, the outer conductor being composed of a plurality of conducting strands insulated from one another so that the internal inductance of said conductor will be materially greater than zero and the ratio of the resistance of the stranded conductor to a non-stranded conductor of the same size will be substantially less than unity, the ratio of the inner diameter of said outer conductor to the outer diameter of the inner conductor being functions of the resistance ratio of stranded to non-stranded conductor and of the internal inductance of the conductor system, said diameter ratio having such a value between 3.2 and 3.6 as will produce minimum attenuation.

7. A transmission circuit for transmitting frequencies well above the audible range comprising two substantially concentric conductors arranged one inside the other, said conductors being insulated from one another and being connected one as a return for the other, each of said conductors being composed of a plurality of conducting strands insulated from one another so that the internal inductance of said conductors will be materially greater than zero and the ratio of the resistance of the stranded conductor to a non-stranded conductor of the same size will be substantially less than unity, the ratio of the inner diameter of the outer conductor to the outer diameter of the inner conductor being functions of the resistance ratio of stranded to non-stranded conductor and of the internal inductance of the conductor system, said diameter ratio having such a value between 3.3 and 4.1 as will produce minimum attenuation.

8. A transmission circuit for transmitting frequencies well above the audible range comprising two substantially concentric conductors arranged one inside the other and connected one as a return for the other, said conductors being insulated from one another by a medium which introduces substantially no dielectric loss, the inner conductor being composed of a plurality of conducting strands insulated from one another so that the internal inductance of said conductor will be materially greater than zero and the ratio of the resistance of the stranded conductor to a non-stranded conductor of the same size will be substantially less than unity, the ratio of the inner diameter of the outer conductor to the outer diameter of said inner conductor being functions of the resistance ratio of stranded to non-stranded conductor and of the internal inductance of the conductor system, said diameter ratio having such a value between 3.3 and 4.3 as will produce minimum attenuation.

9. A transmission circuit for transmitting frequencies well above the audible range comprising two substantially concentric conductors ar-

ranged one inside the other and connected one as a return for the other, said conductors being insulated from one another by a medium which introduces substantially no dielectric loss, each of said conductors being composed of a plurality of conducting strands insulated from one another so that the internal inductance of said conductor will be materially greater than zero and the ratio of the resistance of the stranded conductor to a non-stranded conductor of the same size will be substantially less than unity, the ratio of the inner diameter of the outer conductor to the outer diameter of the inner conductor being functions of the resistance ratio of stranded to non-stranded conductor and of the internal inductance of the conductor system, said diameter ratio having such a value between 3.3 and 3.6 as will produce minimum attenuation.

10. A transmission circuit for transmitting frequencies well above the audible range comprising two substantially concentric conductors arranged one inside the other and connected one as a return for the other, said conductors being insulated from one another by a medium which introduces dielectric loss, the inner conductor being composed of a plurality of conducting strands insulated from one another so that the internal inductance of said conductor will be materially greater than zero and the ratio of the resistance of the stranded conductor to a non-stranded conductor of the same size will be substantially less than unity, the ratio of the inner diameter of the outer conductor to the outer diameter of said inner conductor being functions of the resistance ratio of stranded to non-stranded conductor and of the internal inductance of the conductor system, said diameter ratio having such a value between 3.3 and 4.7 as will produce minimum attenuation.

11. A transmission circuit for transmitting frequencies well above the audible range comprising two substantially concentric conductors arranged one inside the other and connected one as a return for the other, said conductors being insulated from one another by a medium which introduces dielectric loss, each of said conductors being composed of a plurality of conducting strands insulated from one another so that the internal inductance of said conductor will be materially greater than zero and the ratio of the resistance of the stranded conductor to a non-stranded conductor of the same size will be substantially less than unity, the ratio of the inner diameter of the outer conductor to the outer diameter of the inner conductor being functions of the resistance ratio of stranded to non-stranded conductor and of the internal inductance of the conductor system, said diameter ratio having such a value between 3.3 and 4.1 as will produce minimum attenuation.

12. A circuit for the transmission of a band of frequencies extending up to a frequency many times the limit of audibility, said circuit comprising two substantially concentric conductors arranged one inside the other, said conductors being insulated from one another and being connected one as a return for the other, at least one of said conductors being subdivided into conductive units, said units being insulated from one another and being so transposed as to distribute the current substantially uniformly over the cross-section occupied by said units at frequencies lying in said band of frequencies, the ratio of the inner diameter of the outer conductor to the outer diameter of the inner conductor being

such that the attenuation of said circuit will be a minimum at a frequency in said band of frequencies.

13. A transmission circuit for transmitting frequencies well above the audible range comprising two substantially concentric conductors arranged one inside the other, said conductors being insulated from one another and being connected one as a return for the other, at least one of said conductors being subdivided into conductive units, said units being insulated from one another and being so transposed as to distribute the current substantially uniformly over the cross-section occupied by said units at frequencies extending up to many times the limit of audibility, whereby the internal inductance of said conductor will be materially greater than zero and the ratio of the resistance of the stranded conductor to a non-stranded conductor of the same size will be substantially less than unity, the ratio of the inner diameter of the outer conductor to the outer diameter of the inner conductor being functions of the resistance ratio of stranded to non-stranded conductor and of the internal inductance of the conductor system, said diameter ratio having such a value between 3.2 and 4.7 as will produce minimum attenuation.

14. A transmission circuit for transmitting frequencies lying well above the audible range comprising two substantially concentric conductors arranged one inside the other and connected one as a return for the other, said conductors being insulated from one another by a medium which introduces substantially no dielectric loss, the inner conductor being composed of a plurality of conducting strands insulated from one another, the relations in said circuit being expressed by the equation

$$\frac{2nx \log_e x}{nx+1} = \frac{4 \log_e x + L_i}{2 \log_e x + L_i}$$

wherein n is the ratio of the high frequency resistance of said inner conductor to the resistance at the same frequency of a non-stranded conductor of the same dimensions, x is the ratio of the inner radius of the outer conductor to the outer radius of said inner conductor, and L_i is the internal inductance of said inner conductor.

15. A transmission circuit for transmitting frequencies lying well above the audible range comprising two substantially concentric conductors arranged one inside the other and connected one as a return for the other, said conductors being insulated from one another by a medium which introduces substantially no dielectric loss, each of said conductors being composed of a plurality of conducting strands insulated from one another, the relations in said circuit being expressed by the equation

$$\frac{2nx \log_e x}{nx+m} = \frac{4 \log_e x + L'}{2 \log_e x + L'}$$

wherein n is the ratio of the high frequency resistance of the inner conductor to the resistance at the same frequency of a non-stranded conductor of the same dimensions, m is the ratio of the high frequency resistance of the outer conductor to the resistance at the same frequency of a non-stranded conductor of the same dimensions, x is the ratio of the inner radius of said outer conductor to the outer radius of said inner conductor, and L' is the sum of the internal inductances of said inner conductor and said outer conductor.

16. A transmission circuit for transmitting frequencies lying well above the audible range comprising two substantially concentric conductors

arranged one inside the other and connected one as a return for the other, said conductors being insulated from one another by a medium which introduces dielectric loss, the inner conductor being composed of a plurality of conducting strands insulated from one another, the relations in said circuit being expressed by the equation

$$2nx \log_e x - (nx+1) \frac{4 \log_e x + L_i}{2 \log_e x + L_i} - 2\pi c p \sqrt{f \lambda} L_i = 0$$

wherein n is the ratio of the high frequency resistance of said inner conductor to the resistance at the same frequency of a non-stranded conductor of the same dimensions, x is the ratio of the inner radius of the outer conductor to the outer radius of said inner conductor, L_i is the internal inductance of said inner conductor, c is the inner radius of said outer conductor, p is the average power factor of the dielectric medium, f is the frequency, and λ is the conductivity of the conductor material.

17. A transmission circuit for transmitting frequencies lying well above the audible range comprising two substantially concentric conductors arranged one inside the other and connected one as a return for the other, said conductors being insulated from one another by a medium which introduces dielectric loss, each of said conductors being composed of a plurality of conducting strands insulated from one another, the relations in said circuit being expressed by the equation

$$2nx \log_e x - (nx+m) \frac{4 \log_e x + L'}{2 \log_e x + L'} - 2\pi c p \sqrt{f \lambda} L' = 0$$

wherein n is the ratio of the high frequency resistance of the inner conductor to the resistance at the same frequency of a non-stranded conductor of the same dimensions, m is the ratio of the high frequency resistance of the inner conductor to the resistance at the same frequency of a non-stranded conductor of the same dimensions, x is the ratio of the inner radius of said outer conductor to the outer radius of said inner conductor, L' is the sum of the internal inductances of said inner conductor and said outer conductor, c is the inner radius of said outer conductor, p is the average power factor of the dielectric medium, f is the frequency and λ is the conductivity of the conductor material.

18. A coaxial conductor transmission system comprising inner and outer conductors of different effective resistivities, at least one of these conductors being a composite structure, the ratio of the internal diameter of the outer conductor to the external diameter of the inner conductor being the optimum with respect to the attenuation of waves lying near the top of the frequency band transmitted.

19. A transmission circuit for transmitting frequencies lying well above the audible range comprising two substantially concentric conductors arranged one inside the other, said conductors being insulated from one another and being connected one as a return for the other, at least one of said conductors being a composite structure so that the effective resistivities of the two conductors will be different, the ratio of the inner diameter of the outer conductor to the outer diameter of the inner conductor being so related to the resistance ratio of the two conductors that the attenuation of their circuit at a given high frequency transmitted thereover will be a minimum.

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