

March 17, 1936.

E. I. GREEN ET AL

2,034,033

SHIELDED STRANDED PAIR

Filed June 7, 1933

3 Sheets-Sheet 1

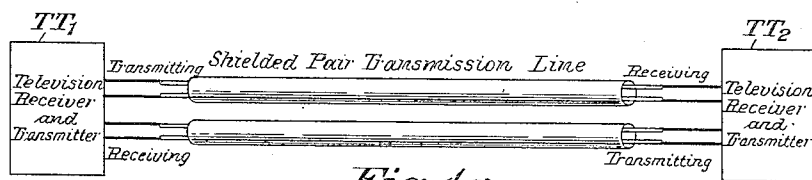


Fig. 1a

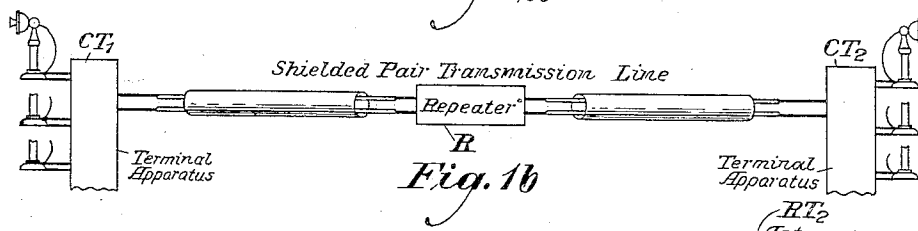


Fig. 1b

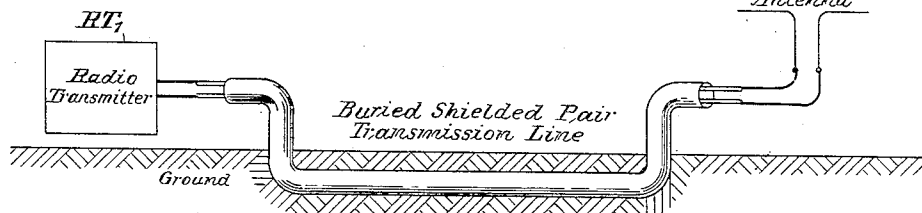


Fig. 1c

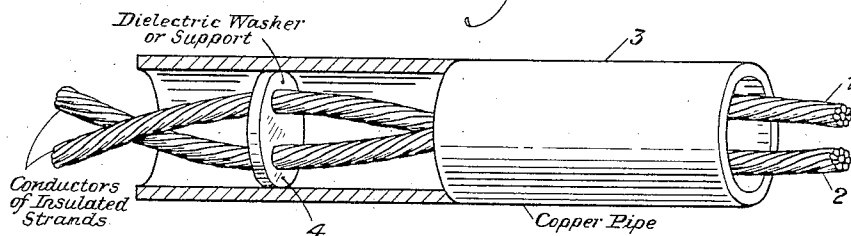


Fig. 2

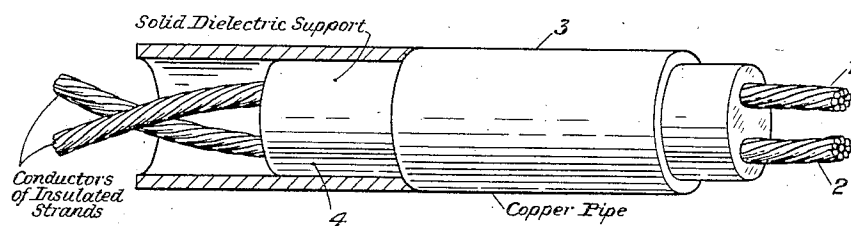


Fig. 3

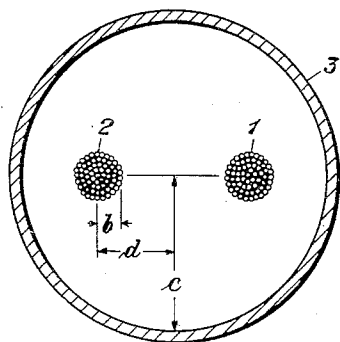


Fig. 4

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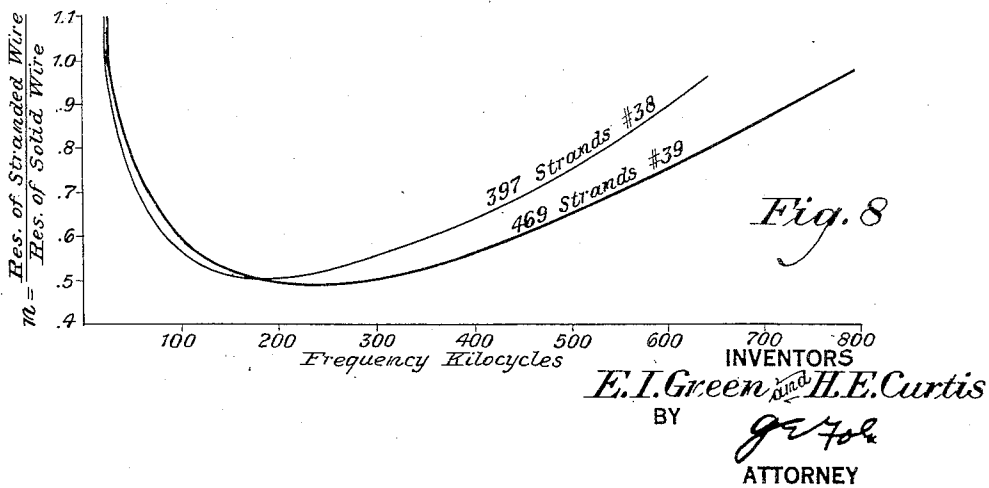
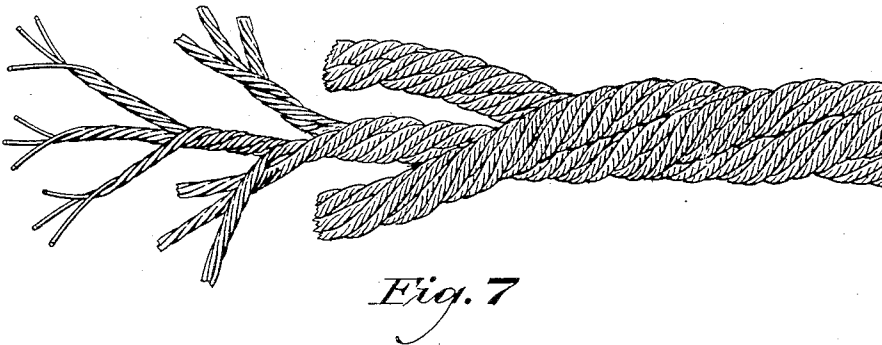
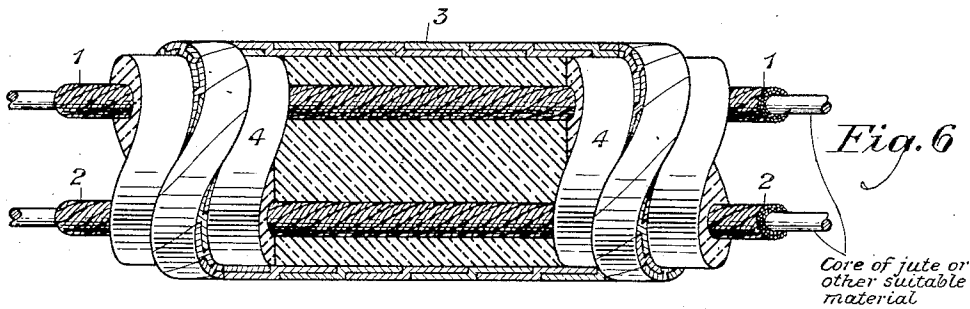
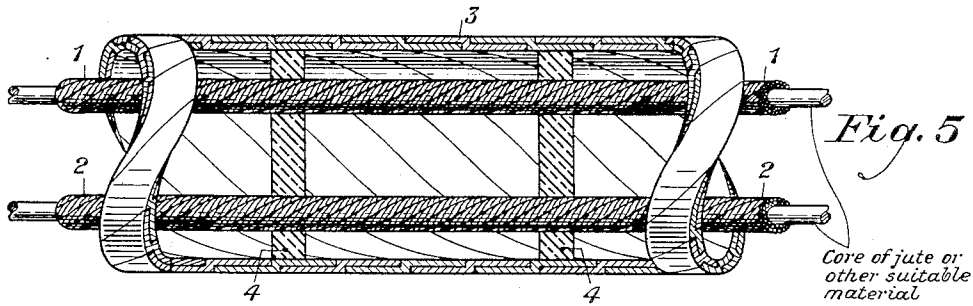
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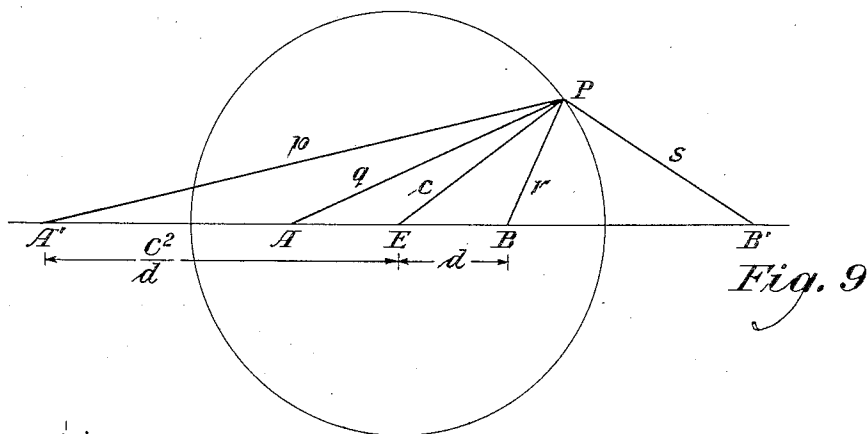


Fig. 9

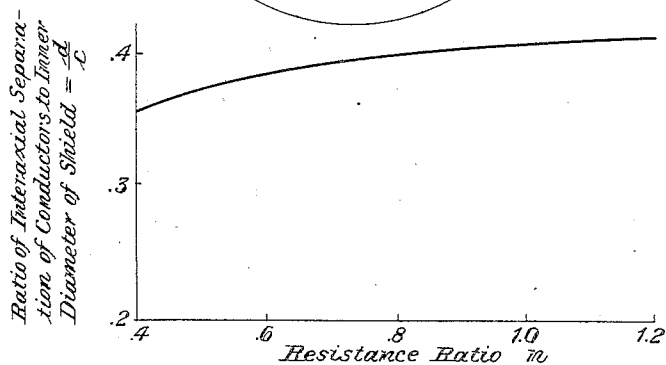


Fig. 10

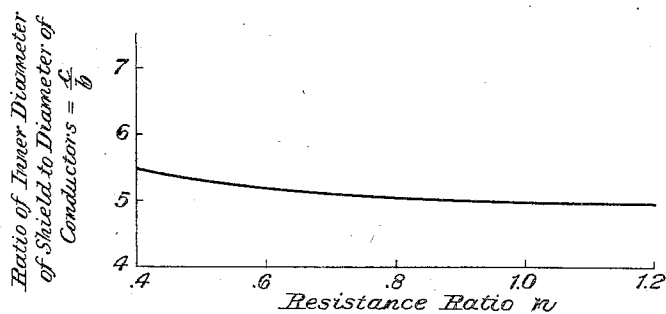


Fig. 11

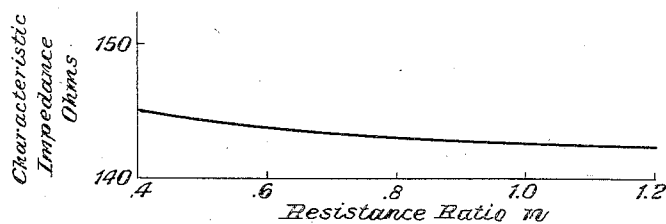


Fig. 12

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UNITED STATES PATENT OFFICE

2,034,033

SHIELDED STRANDED PAIR

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York

Application June 7, 1933, Serial No. 674,763

15 Claims. (Cl. 178-44)

This invention relates to electrical transmission circuits and is concerned especially with circuits comprising a pair of conductors surrounded by an individual shield. A particular object of the invention is to obtain an individually shielded circuit which has the properties of low attenuation and substantial freedom from external induction throughout a wide range of frequencies. Another object of the invention is to obtain a circuit of such characteristics which is balanced with respect to ground.

The frequency range which may be transmitted over a circuit consisting of an ordinary unshielded pair of conductors is limited both by the increasing susceptibility of the circuit to crosstalk from nearby conductors and interference from external sources as the frequency is increased, and also, in many instances, by the large high frequency attenuation which results from the use of solid dielectric material. In accordance with the invention it is proposed to enclose a pair of conductors in a conducting shield which acts to prevent external electromagnetic or electro-static disturbances from causing disturbances in the pair, and conversely, to prevent the currents transmitted over the pair from causing disturbances in external circuits. Moreover, since the shielding effect of such an enclosing shield decreases as the frequency decreases, it is proposed in accordance with the invention to twist the conductors of the pair helically about the axis of the shield or otherwise transpose them in order to annul any interference which may pass through the shield at low frequencies.

In order to reduce the high frequency attenuation of the shielded pair it is proposed in one embodiment of the invention to employ a substantially gaseous dielectric between the conductors of the pair and between these conductors and the surrounding sheath. The invention comprehends also, however, the use of non-gaseous dielectric material to insulate the conductors from one another and from the sheath.

The invention has to do especially with individually shielded pairs of conductors in which each conductor is constituted of a number of insulated strands or filaments which are so interwoven or arranged as to reduce the high frequency resistance of the circuit. Pairs of conductors which are surrounded by shields of substantially circular cross-section are a particular subject of the invention.

A particular object of the invention is to so proportion the ratio of the inner diameter of the shield to the diameter of the conductors and the ratio of the interaxial separation between conductors to the inner diameter of the shield that, for any given degree of stranding and for a given size of shield, the attenuation will be a minimum. More broadly, the invention is concerned with

systems for utilizing individually shielded balanced pairs for the transmission of high frequencies or wide bands of frequencies. Satisfactory transmission of television images with good definition requires the transmission of a frequency band which may extend from zero frequency to hundreds or even thousands of kilocycles. If, for example, it is desired to transmit with a total of 24 reproductions per second an image containing 40,000 picture elements, there is required a frequency band of approximately 500 kilocycles in width. Still wider bands may be necessary for representing with adequate detail such scenes as a theatrical performance or an athletic event. A shielded transposed pair designed in accordance with the principles of the invention is especially suited for the transmission of such television bands because it may be given comparatively low attenuation and relative freedom from interference over the entire band.

Moreover, by the application of multiplexing the wide frequency bands obtainable from the shielded transposed pair may be used to provide substantial numbers of narrower frequency bands suitable for other uses, as for example, for telephone circuits which may require bands of about 2500 cycles in width, for high quality program circuits which may require bands extending up to 10,000 cycles or higher, for high speed facsimile transmission, or for other purposes.

Inasmuch as the two conductors are symmetrical at all points with respect to the shield, the potential between each conductor and the shield is equal. Therefore, if such a shielded stranded pair were buried so that the shield makes electrical contact with the ground, or if the shield were electrically connected to ground at frequent intervals, the two conductors would form a balanced-to-ground circuit. Even if the shield were not connected by wires to ground or buried, it would be effectively connected to ground due to the electrical capacity between it and ground. Hence, the two conductors will always form a balanced-to-ground circuit. Such a balanced-to-ground circuit would be very useful for interconnecting electrical elements which are themselves balanced to ground.

For instance, it is frequently desirable in the radio art to employ an antenna which is balanced with respect to ground rather than to connect, transmit or receive between antenna and ground. Such, for example, is the case when using a diamond antenna or a horizontal dipole antenna. A shielded twisted pair of the type described herein is peculiarly adapted for connecting such balanced antennas with radio transmitting or receiving apparatus inasmuch as such a pair may be balanced to ground and may be designed to have low attenuation and substantial immunity

from external interference at the frequency or frequencies employed for radio transmission.

These and other objects and features of the invention will be more readily understood from the following description when read in connection with the accompanying drawings, in which Fig. 1A, 1B and 1C represent various transmission systems utilizing shielded stranded pairs; Figs. 2, 3, 4, 5 and 6 are sections of various shielded stranded pairs; Fig. 7 is a view of a stranded conductor; Fig. 8 shows the ratio of the resistance of a stranded conductor to the resistance of a solid conductor of the same diameter versus frequency for two conditions of stranding; Fig. 9 is a section of a shielded stranded pair; Figs. 10 and 11 are curves indicating the optimum proportioning of a shielded stranded pair to obtain minimum high frequency attenuation; and Fig. 12 shows the characteristic impedance of a shielded pair having optimum proportioning for high frequency transmission.

Overall systems embodying the invention are schematically illustrated in Figs. 1A, 7B and 1C. In these figures shielded pair transmission lines are shown associated with various kinds of apparatus at the terminals. Thus in Fig. 1A is shown a pair of wide band television transmitters and receivers, indicated at TT₁ and TT₂, respectively, connected to the terminals of two shielded stranded pairs. Fig. 1B shows a shielded pair utilized in a carrier telephone system. The terminal apparatus CT₁ and CT₂ connected to the shielded pair may consist of modulators, demodulators, filters and amplifiers. A repeater R is shown between two sections of the shielded pair line. Fig. 1C shows a shielded pair transmission line used to connect a radio transmitter RT₁ to a balanced-to-ground radio antenna RT₂, for example, a horizontal dipole. If desired, the shield can be buried as shown in Fig. 1C.

Referring to Fig. 2, 1 and 2 represent two conductors formed of insulated strands, said conductors being held in proper relation and out of electrical contact with each other and with the circular conducting shield 3 by means of spaced dielectric washers 4. These washers should be separated from each other a suitable distance and should be made as thin as possible consistent with the required mechanical strength. They should also be composed of some dielectric material of small loss angle and low dielectric constant, for if these conditions are obtained, the leakage loss may be made so small as to be practically negligible. Fig. 3 shows a longitudinal section through a shielded stranded pair having solid dielectric; 1 and 2 are the two conductors formed of insulated strands, 3 is a circular shield of conducting material such as a copper pipe, and 4 is a solid dielectric washer by means of which the conductors and shield are held in proper relation. This solid dielectric should preferably have a small loss angle and low dielectric constant in order to make the attenuation as low as possible. For example, "Paragutta" or other similar insulating material may be used for the dielectric 4.

Fig. 4 represents a cross-sectional view of a shielded stranded pair; 1 and 2 are conductors composed of a number of insulated strands, and 3 represents the circular conducting shield. In Fig. 4, *c* represents the inner radius of the shield, *d* one-half the interaxial separation of the two stranded conductors 1 and 2, and *b* represents the radius of the conductors. Figs. 5 and 6 are longitudinal sections of a shielded pair. 1 and 2

are conductors composed of a number of insulated strands twisted so as to form a conductor of annular cross-section, the core of the conductors being filled with some non-conducting material as jute or a conducting material such as copper or steel. 3 is the conducting shield in the form of a tube composed of overlapping tapes of Z-shaped cross-section. The dielectric 4 in Fig. 5 is in the form of thin insulating washers; that in Fig. 6 is a solid dielectric such as paragutta.

The conductors may consist of a number of strands, filaments, tapes, or the like, which are insulated from one another and are interwoven or braided together in any of various ways. Ordinarily the purpose of such stranding would be to reduce the resistance of the conductors at high frequencies by counteracting the tendency of the currents to concentrate on the surface of the conductor and thereby to decrease the high frequency attenuation of the circuit. Another important result obtained by stranding, however, is an increase in the internal inductance of each conductor which likewise reduces the high frequency attenuation. Stranding may also be advantageous from the standpoint of obtaining a flexible structure.

In order to counteract the tendency of the currents to concentrate on the surface of the conductor at high frequencies, it is essential that the insulated strands be passed back and forth toward and from the center of the conductor. With a suitable method of stranding, the high frequency current may be distributed substantially uniformly over the cross-section of the conductor. One method of obtaining this result is to strand the conductor in a manner similar to that used in the manufacture of rope. Thus, several individual strands (for example, three) would first be twisted together, next several of these groups would be twisted together to form larger groups, and several of the larger groups would be twisted together, the process being continued until the desired total number of strands is obtained. If the stranding interval or pitch is made different for the successive twisting operations, it will be found that with such a procedure any one strand in going along the conductor travels a path back and forth between the center of the conductor and its periphery. A stranded conductor built up in this manner is illustrated in Fig. 7.

Instead of twisting the strands as described above they might be interwoven or braided in other ways so as to produce the same effect. Also, it would be possible to employ an annular cross-section for the insulated strands, the core of the conductor being filled up with some non-conducting material such as jute, or with a conducting material such as copper or steel to provide rigidity or strength as shown in Figs. 5 and 6. The stranding might be arranged in such a way that the path of any strand would extend between the outer and inner circumferences of the annulus.

The two conductors may be either parallel or transposed at frequent intervals. One method of transposition would be to twist the two conductors helically about the axis of the shield. As will be brought out below, the optimum proportioning of the circuit will be the same in either case.

For the insulation between the two conductors and between conductors and sheath, any of various forms or shapes may be employed. One possible arrangement would be to use a continuous spirally applied string or strip of dielectric

material. Generally, it will be desirable that the amount of insulating material employed be a minimum in order that the dielectric between the two conductors may be largely gaseous. In some instances, however, it may be found advantageous to use a dielectric which is partly or wholly non-gaseous, as, for example, rubber insulation, as illustrated in Figs. 3 and 6.

The shield surrounding the two conductors, instead of being formed of a single tube, might consist of a cylindrical assembly of conducting strips, tapes, ribbons, wires, or the like. Such forms of construction might be particularly advantageous where a flexible structure is desired.

In connection with the shield it may be noted that in addition to performing an electrical function by protecting the circuit from external induction, it may be useful in affording mechanical protection to the circuit and thereby permitting the use of air dielectric to a very considerable extent. Due to skin effect the high-frequency currents will penetrate very little into the shield so that the electrical requirements are satisfied by a very thin shield. Consequently, the thickness of the shield will ordinarily be determined by mechanical considerations. The thickness of the shield will usually be such that it does not enter into the problem of determining the optimum configuration of conductors and shield.

The use of the shield will ordinarily make it possible where desired to allow the signals transmitted over the pair to drop down to a minimum level determined by the noise due to thermal agitation of electricity in the conductors. Hence the use of the shield may facilitate the spacing of intermediate amplifiers in the circuit at wider intervals than would otherwise be possible.

The configuration of the conductors and shield which results in minimum high frequency attenuation can be determined by obtaining an expression for the attenuation of the system and then determining the diameter and spacing ratios which make the attenuation a minimum for any given inner diameter of the shield. It will be assumed that the frequency is above the audible range and that the leakage is zero (a condition that may be approximately obtained). All units are in the c. g. s. electromagnetic system.

The attenuation at high frequencies of an electrically smooth transmission line with zero leakage is given very closely by the expression

$$\frac{R}{2} \sqrt{\frac{C_1}{L}}$$

where R represents the resistance, C_1 the capacitance and L the inductance of the system. The total resistance R of the system is made up of the resistance of the stranded conductors with the shield absent and the resistance due to eddy current loss in the conducting sheath, proximity effect between the two conductors being eliminated by stranding. The high frequency resistance (in abohms per centimeter) of the two stranded conductors without the shield may be written as

$$\frac{2n}{b} \sqrt{\frac{f}{\lambda}}$$

b being the radius of the conductors, f the frequency in cycles, λ the conductivity of the shield material (approximately 5.8×10^{-4} abohms per cm. cube for copper), and n the ratio of the resistance at the same frequency of the stranded conductor to the resistance of a solid conductor of the same outer diameter but of a conductivity

equal to that of the shield. The value of n for a conductor that is completely stranded, i. e. so stranded that the current density is uniform throughout the entire cross-section, can be obtained from a formula by S. Butterworth 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 which involve D^2 , when it will read

$$R' = R_0 \left[\left(1 + \frac{\alpha^2}{2} \right) (1 + F) + \frac{2S^2 \delta^2 G}{d^6} \right] \quad (1)$$

This gives the A. C. resistance of a completely stranded conductor in abohms per centimeter. The meanings of the various symbols and the reason for omission of the two terms mentioned above will be found in the article. The high frequency resistance R_1' of a solid wire (in abohms per centimeter) is given by the expression

$$\frac{1}{b} \sqrt{\frac{f}{\lambda}}$$

The value of n can be determined by dividing R' by R_1' . Fig. 8 shows how n varies with frequency for two conditions of stranding when all of the conductors are of copper.

For any completely stranded conductor there is ordinarily a frequency at which the ratio n is a minimum. The lowest value of n that can be obtained for a completely stranded conductor of a given diameter and size of strands together with the number of strands and the thickness of insulation necessary to produce this value of n can be determined by Expression 1. The conductors should be designed so as to have as low a value of n as possible at the given frequency, and the size and separation of the conductors should be determined for this minimum value of n if it is desired to obtain as low an attenuation as possible at a given frequency for a shield of given diameter and material.

If the conductors are not completely stranded, the value of n may be determined either by computation or experiment.

The increment in the resistance of the two stranded conductors due to the current in the conducting sheath may be obtained in the following manner. Referring to Fig. 9, let points A and B represent the centers of the two stranded wires each spaced a distance d from E which is the center of the sheath having a radius c . The effect of the sheath may be replaced by the two image wires A' and B', each spaced a distance

$$\frac{c^2}{d}$$

from E as described on page 174, Radio Frequency Measurements (1931), E. B. Moullin.

From a consideration of the magnetic fields due to the conductors and their images, the tangential magnetic field intensity at any point P on the sheath can be shown to be

$$H = \frac{2I(c^2 - d^2)}{c} \left[\frac{1}{c^2 + d^2 - 2cd \cos \theta} - \frac{1}{c^2 + d^2 + 2cd \cos \theta} \right] \quad (2)$$

where H is the magnetic field intensity, I is the current in the conductors and θ the angle PEB (Fig. 9). The normal component at P is zero. At high frequencies the field outside the shield is substantially zero, so we can assume a current in the shield producing a field equal and opposite that due to the conductors and their images.

Therefore the current density N at P equals $C_2 H$ where C_2 is a constant.

In a given material the power loss in the sheath is proportional to N^2 and to the area; thus the power loss in the sheath per unit length is

$$W_1 = \int_0^{2\pi} C_3 N^2 c d\theta = c C_3^2 C_2 \int_0^{2\pi} H^2 d\theta \quad (3)$$

Where

W = power loss in the sheath per unit length
 C_3 = constant, c = radius of sheath.

Into this expression for the power loss we can place the expression for the field H at the point P : thus

$$W_1 = \frac{4I^2(c^2 - d^2)^2 C_2^2 C_3}{c} \int_0^{2\pi} \left(\frac{1}{c^2 + d^2 - 2cd \cos \theta} - \frac{1}{c^2 + d^2 + 2cd \cos \theta} \right) d\theta \quad (4)$$

This becomes:

$$W_1 = 64I^2 \pi \frac{cd^2 C_2^2 C_3}{c^4 - d^4} \quad (5)$$

By the same method we may obtain the power loss in the circular sheath of radius c when used as a concentric return for a wire placed in its center. Thus the field

$$H_1 = \frac{2I}{c}$$

The current density N_1 is proportional to H_1 . For the same frequency and material as above

$$W_2 = \int_0^{2\pi} C_3 N_1^2 c d\theta = \frac{8I^2 \pi C_2^2 C_3}{c} \quad (6)$$

The ratio of the resistance R_1 which the sheath introduces in the circuit consisting of the two stranded wires to the resistance R_2 which the sheath would have if used as a concentric return is then at high frequencies

$$\frac{R_1}{R_2} = \frac{W_1}{W_2} = \frac{8c^2 d^2}{c^4 - d^4} \text{ or } R_1 = \frac{8c^2 d^2}{(c^4 - d^4)} R_2 \quad (7), (8)$$

The high frequency resistance R_2 of the shield when used as a concentric return for an inner conductor is given by the well known expression

$$R_2 = \frac{1}{c} \sqrt{\frac{f}{\lambda}} \quad (9)$$

Therefore the total resistance R of the shield pair is

$$2 \sqrt{\frac{f}{\lambda} \left(\frac{n}{b} + \frac{4cd^2}{b + c^4 - d^4} \right)} \quad (10)$$

The capacity between two completely stranded wires when surrounded by a cylindrical metallic sheath is given by the expression:

$$\frac{K}{4 \log_e \left(\frac{2d}{b} \right) \left(\frac{c^2 - d^2}{c^2 + d^2} \right)} \quad (11)$$

The inductance of the system is made up of the inductance due to the magnetic field outside the conductors and the internal inductance due to the flux within the conductors. The external inductance equals the reciprocal of the capacity of the circuit multiplied by the dielectric constant K . The internal inductance is a function of the distribution of the flux in the conductors. For stranded conductors the internal inductance at high frequencies is approximately that at direct current in so much as the current distribution is relatively independent of frequency up to very high frequencies. The internal inductance of a pair of completely stranded conductors is then one

abohm per centimeter. The total inductance becomes:

$$L = 4 \log_e \left[\frac{2d}{b} \left(\frac{c^2 - d^2}{c^2 + d^2} \right) \right] + 1 \quad (12)$$

Therefore the attenuation at high frequencies and for zero leakage is

$$\frac{\sqrt{K} \sqrt{\frac{f}{\lambda}}}{2c} \sqrt{\log_e \frac{\left[\frac{nc}{b} + \frac{4 \frac{d^2}{c^2}}{1 - \frac{d^4}{c^4}} \right]}{M(4 \log_e M + 1)}} \quad (13)$$

where

$$M = \frac{2d}{b} \frac{1 - \frac{d^2}{c^2}}{1 + \frac{d^2}{c^2}} \quad (14)$$

For any given value of shield radius c , the values of b and d which give minimum attenuation may be found by setting

$$\frac{\delta A}{\delta b} = 0; \quad \frac{\delta A}{\delta d} = 0 \quad (15) (16)$$

On imposing the first condition we find that

$$-\frac{b^2 \delta M}{n \delta b} = M \frac{2 \log_e M(4 \log_e M + 1)}{8 \log_e M + 1} \frac{1}{\frac{n}{b} + \frac{4cd^2}{c^4 - d^4}} \quad (17)$$

Imposing the second condition we find that

$$\frac{\delta M}{\delta d} \frac{(c^4 - d^4)^2}{8cd(c^4 + d^4)} = M \frac{2 \log_e M(4 \log_e M + 1)}{8 \log_e (M + 1)} \frac{1}{\frac{n}{b} + \frac{4cd^2}{c^4 - d^4}} \quad (18)$$

Combining the left-hand members of Equations (17) and (18) and substituting the values of the derivatives, the following expression results

$$\frac{c}{b} = \frac{8 \frac{d^2}{c^2} \left(1 + \frac{d^4}{c^4} \right)}{n \left(1 - \frac{d^4}{c^4} \right) \left(1 - 4 \frac{d^2}{c^2} - \frac{d^4}{c^4} \right)} \quad (19)$$

This expression is the locus of values of the diameter ratio

$$\frac{c}{b}$$

which give minimum attenuation for different assumed values of the wire spacing ratio

$$\frac{d}{c}$$

The unique values of

$$\frac{d}{c} \text{ and } \frac{c}{b}$$

which give minimum attenuation for a given resistance ratio n are obtained by taking pairs of

$$\frac{d}{c} \text{ and } \frac{c}{b}$$

which satisfy Equation (19) and substituting them in Expression (13) for the attenuation and graphically determining the pair that gives minimum attenuation.

Fig. 10 shows graphically the relation that should exist between the spacing ratio

$$\frac{d}{c}$$

and the resistance ratio n for minimum atten-

uation for any predetermined inner diameter of shield. The relationship between

$$\frac{d}{c}$$

and n as indicated by the curve of Fig. 10 can be approximated closely by the empirical expression

$$\frac{d}{c} = 0.425\sqrt{n}$$

The relationship that should exist between

$$\frac{c}{b}$$

and n for minimum attenuation for any predetermined inner diameter of shield is shown in Fig. 11. This relationship can be approximated closely by the empirical expression

$$\frac{c}{b} = \frac{4.5}{4.5\sqrt{n}} + \frac{1}{2}n^{2.8}$$

It can be seen moreover by examination of Figs. 10 and 11 that for the values of n lying between about 0.5 and 1.11 the ratio

$$\frac{d}{c}$$

can be approximated roughly by 0.40 and

$$\frac{c}{b}$$

by 5.0 irrespective of the value of n .

However, if it is desired to design a shielded stranded pair so that the attenuation will be more exactly a minimum for any particular value of n , the relations given in Figs. 10 and 11 or the equivalent empirical expressions given above should be used.

It must be borne in mind that the value of n to be used in designing a shielded stranded pair is the value that is given by the maximum frequency to be transmitted over the transmission line. If any given shielded stranded pair is designed in the above manner, the attenuation at the maximum frequency will be as low as possible at this frequency. At any lower frequency the system will not have the optimum design but since the attenuation is less at the lower frequencies, this fact does not matter. The same value of n determines both ratios.

$$\frac{d}{c} \text{ and } \frac{c}{b}$$

The high frequency impedance of such a conductor system is given closely by the expression

$$\sqrt{\frac{L}{C_1}}$$

Hence proportioning the conductors in such a manner as to obtain minimum high frequency attenuation as disclosed above results in a certain high frequency characteristic impedance

$$\alpha = \frac{\sqrt{\frac{1}{9} \times 10^{-20}} \sqrt{\frac{300,000}{5.8 \times 10^{-4}}}}{2 \times .250'' \times 2.54} \times$$

$$\left[\frac{.47 \times 5.4 + 4 \frac{.365^2}{1 - .365^4}}{\sqrt{\left(\log_e 2 \times 5.4 \times .365 \frac{1 - .365^2}{1 + .365^2} \right) \left(4 \log_e \left(2 \times 5.4 \times .365 \left(\frac{1 - .365^2}{1 + .365^2} \right) + 1 \right) \right)}} \right] \times$$

$$[2.54 \times 12 \times 5280 \times 8.686] = 1.075 \text{ db per mile}$$

corresponding to each value of n . This relation between the characteristic impedance and n is shown on Fig. 12. The characteristic impedance for minimum attenuation is approximately 143 ohms for the usual values of n .

Example

The proportioning of shielded pair circuits so as to secure with a given size shield the lowest possible attenuation at a given maximum frequency is complicated slightly by the fact that the size of the conductors for a given diameter of shield depends on the value of n , and the lowest value of n attainable at a given frequency depends upon the size of the conductor as well as other quantities. Hence the method of designing such a circuit is one of successive approximations. To illustrate this method a simple example will be considered. Thus it may be desired to so proportion a shielded pair circuit of copper whose shield is to be .500'' in inner diameter and whose enclosed conductors are to be completely stranded and composed of No. 40 B. & S. gauge strands, that the attenuation at 300 kc. will be as low as possible. From Fig. 11 it can be determined that the conductor should be approximately $\frac{1}{2}$ the diameter of the shield, i. e., .100'' in diameter. From Expression (1) it can be determined that the lowest value of n attainable for this diameter under the above conditions is .46. Considering Fig. 11 again it is seen that the diameter ratio should have been more exactly 5.4; hence the conductor diameter becomes

$$\frac{.500}{5.4} = .093''$$

For this sized conductor the lowest value of n for the given conditions of frequency and strand size is .47.

From Fig. 11 it is seen that the optimum diameter ratio changes little from $n=.46$ to $n=.47$. Hence the conductor diameter should be approximately .093''. From a consideration of Expression (1) it can be determined that the minimum value of n for a .093'' conductor composed of No. 40 B. & S. strands is obtainable by using approximately 500 strands, each strand having an insulation thickness 20% the radius of the strand. From Fig. 10 it can be determined that the ratio of interaxial separation of the conductors to the inner diameter of the shield should be approximately .365. Hence the interaxial separation of the conductors should be approximately $.093'' \times .365 = .182''$. The design of such a circuit for any other size shield, maximum frequency and size of strand can be carried out similarly.

The attenuation of shielded pair circuit as proportioned in the previous paragraphs can be obtained from Expression (13). Substituting numerical values in the expression and changing from c. g. s. absolute units to practical units we obtain

Such a transmission circuit when used in connection with a carrier telephone system utilizing repeaters having, for example, 60 db gain would enable the repeater stations to be spaced approximately 57 miles apart.

If the conductors are not completely stranded, the inductance is no longer given by Expression (12) but becomes

$$4 \log_e \frac{2d}{b} \frac{c^2 - d^2}{c^2 - d^2} + L_0 \quad (19)$$

where L_0 is the internal inductance of the two conductors in abhenries per centimeter. Therefore Expression (13) for the attenuation of the system becomes a

$$\sqrt{K} \sqrt{\frac{f}{\lambda}} \frac{\frac{nc}{b} + \frac{4d^2}{c^2}}{1 - \frac{d^4}{c^4}} \frac{1}{2c \sqrt{\log_e M(4 \log_e M + L_0)}} \quad (20)$$

It is difficult to obtain a general solution of this problem, i. e., to determine the value of

$$\frac{c}{b} \text{ and } \frac{d}{c}$$

which gives minimum attenuation for any value of n and L_0 , because the internal inductance of the conductors depends upon the cross-section of the conductors. For example, if the conductors are annular in cross-section, the internal inductance of the two conductors is given by the expression

$$L_0 = 2 \left[\frac{(\rho^2 + 1)}{2(\rho^2 - 1)} - \frac{2}{\rho^2 - 1} + \frac{2}{(\rho^2 - 1)^2} \log_e \rho \right] \quad (21)$$

where

$$\rho = \frac{b}{a}$$

b is the outer radius and a is the inner radius of the stranded annular conductor. For other stranded conductors the internal inductance can be determined either experimentally or by published formulas. The correct proportioning for minimum attenuation for any frequency and conductor cross-section can be determined by putting the corresponding values of L_0 and n into Expression (20) and determining graphically the values of

$$\frac{c}{b} \text{ and } \frac{d}{c}$$

which makes it a minimum for a predetermined value of c .

The high frequency characteristic impedance of a shielded pair system in which the conductors are not completely stranded is approximately

$$\frac{2}{\sqrt{K}} \sqrt{\log_e M(4 \log_e M + L_0)}$$

whereas before M equals

$$\frac{2d}{b} \times \frac{1 - \frac{d^2}{c^2}}{1 + \frac{d^2}{c^2}}$$

In the derivation of the ratios

$$\frac{d}{c} \text{ and } \frac{c}{b}$$

which give minimum attenuation it was assumed that the dielectric loss was negligible. Since in actual practice it would probably be necessary to provide some sort of support to maintain the

conductors and shield in their proper relationship, the insertion of a certain amount of dielectric inside the shield would be necessary. By using as small an amount of dielectric as possible and by using dielectric material with a small dielectric constant and low power factor, the effect of the dielectric on the constants of the line could be made negligible. Accordingly, the diameter ratios and spacing ratios for various values of n would remain as disclosed.

It is possible however, to proportion a shielded pair of predetermined size so that it will have minimum attenuation at any given value of n even though the dielectric loss is large, provided that the average dielectric constant is independent of the proportions of the circuit.

The high frequency attenuation of a smooth line having leakage is given by the expression

$$\frac{R}{2} \sqrt{\frac{C_1}{L}} + \frac{G}{2} \sqrt{\frac{L}{C_1}} \quad (22)$$

where G is the leakage per unit length which in turn is equal to $C_1 \omega P$, C_1 being the capacity per unit length of the system, ω being 2π times the frequency and P the power factor. By the use of Equations (11), (12) and (13), Equation (22) reduces to

$$\frac{\sqrt{K} \sqrt{\frac{f}{\lambda}}}{2c} \left[\frac{\frac{nc}{b} + \frac{4c^2 d^2}{c^4 - d^4}}{\sqrt{\log_e M(4 \log_e M + 1)}} + \frac{2\pi c P \sqrt{f \lambda} \sqrt{1 + \frac{1}{4 \log_e M}}}{\sqrt{\log_e M(4 \log_e M + 1)}} \right] \quad (23)$$

where, as before,

$$M = \frac{2d}{b} \frac{1 - \frac{d^2}{c^2}}{1 + \frac{d^2}{c^2}}$$

λ = conductivity in abmho per centimeter cube and c = inner radius of shield in centimeters. From Equation (23) it is evident that the diameter ratio

$$\frac{c}{b}$$

and spacing ratio

$$\frac{d}{c}$$

that will give minimum attenuation depend on n , P , f , c and λ . By assuming various values for P , f , c and λ , the values of

$$\frac{c}{b} \text{ and } \frac{d}{c}$$

can be determined graphically for any value of n which will make the attenuation as given by Equation (23) a minimum. Doing this for various combinations of P , f , c and λ , it is possible to determine the desired relation between

$$\frac{c}{b}, \frac{d}{c}$$

and n for various values of P , f , c and λ . By comparing these values of

$$\frac{c}{b} \text{ and } \frac{d}{c}$$

to those obtained for wholly gaseous dielectric, it is possible to obtain an empirical relation between the values of

$$\frac{c}{b} \text{ and } \frac{d}{c}$$

which obtains for a system having no dielectric loss and those for systems having appreciable dielectric loss. Thus, it can be shown graphically that the value of

$$\frac{d}{c}$$

is not affected appreciably by the leakage loss in the dielectric. However, the value of

$$\frac{c}{b}$$

to be used for any frequency, power factor and diameter of shield can be obtained approximately by multiplying the value of

$$\frac{c}{b}$$

$$Z_0 = \frac{2}{\sqrt{k}} \sqrt{\left[4 \log_e \left(\frac{2c}{b} \times \frac{d}{c} \times \frac{1 - \frac{d^2}{c^2}}{1 + \frac{d^2}{c^2}} \right) + L_0 \right] \left[\log_e \left(\frac{2c}{b} \times \frac{d}{c} \times \frac{1 - \frac{d^2}{c^2}}{1 + \frac{d^2}{c^2}} \right) \right]}$$

for zero leakage by the expression

$$1 + 1.2\sqrt{f P c \sqrt{\lambda}} (1.1 - n)$$

for values of n less than 1.1.

Thus, for n less than 1.1 the value of

$$\frac{c}{b}$$

for any power factor, frequency and diameter shield for copper conductors is given approximately by the expression

$$\frac{c}{b} = \frac{c_0}{b_0} [1 + .029\sqrt{f P c} (1.1 - n)] \quad (24)$$

where

$$\frac{c_0}{b_0}$$

is the diameter ratio for the case of negligible leakage as shown in Fig. 7. For n greater than 1.1,

$$\frac{c}{b}$$

should be approximately 5;

$$\frac{d}{c}$$

is given approximately by the expression

$$0.42\sqrt[3]{n}$$

regardless of f , P , λ and c .

Inasmuch as the high frequency characteristic impedance of a transmission system is relatively independent of the dielectric loss, the characteristic impedance of a shielded pair system having dielectric loss is equal approximately to the air dielectric characteristic impedance divided by the square root of the average dielectric constant of the insulating medium.

It has been assumed that the two stranded conductors are either parallel or transposed at frequent intervals, maintaining at all points the proper diameter and spacing ratios, except, however, at the transposition points. In the case of the helically twisted type of transposition, the twisting of the conductors does not materially affect the conditions for minimum attenuation providing the twist is relatively long compared with the diameter of the conductors.

At low frequencies at which the shield does not provide adequate electromagnetic shielding, the transposing of the conductors serves to reduce to

a very low amount the resultant disturbance in the circuit due to inadequate shielding. The pair is shielded at high frequencies from outside disturbances and also does not produce any disturbance outside the sheath due to the shielding effect produced by the eddy currents induced in the shield. Thus, a shielded transposed pair is relatively free from external interference at all frequencies and hence is useful and advantageous for the transmission of frequency bands extending down to zero frequency.

The condition that must be satisfied for maximum high frequency characteristic impedance for a shielded stranded pair can also be determined. The high frequency characteristic impedance of a shielded stranded pair is:

The internal inductance L_0 being independent of the diameter ratio

$$\frac{c}{b}$$

and the spacing ratio

$$\frac{d}{c}$$

the ratio

$$\frac{d}{c}$$

for maximum characteristic impedance for any given diameter ratio

$$\frac{c}{b}$$

can be obtained by maximizing the term

$$\frac{d}{c} \times \frac{1 - \frac{d^2}{c^2}}{1 + \frac{d^2}{c^2}}$$

This can be accomplished by taking its derivative with respect to the ratio

$$\frac{d}{c}$$

and putting this derivative equal to zero. Thus we find that

$$\frac{d}{c} = .486$$

for maximum characteristic impedance for any given ratio of inner diameter of shield to diameter of conductor.

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 comprising two cylindrical conductors of substantially the same size arranged side by side and spaced apart, a cylindrical conducting shield surrounding said conductors, one of said conductors being connected as a return for the other to form a high frequency transmission path shielded by said shield, said conductors and shield being insulated from one another by a substantially gaseous dielectric, each of said conductors consisting of a plurality of conducting strands insulated from

one another and so stranded that current distribution is substantially uniform for a range of frequencies extending to a region well above audibility, the transmission path formed from said cylindrical conductors acting one as a return for the other, having connected thereto apparatus for applying thereto and receiving and utilizing therefrom a band of signal frequencies extending from approximately zero to a frequency many times the upper limit of the audible range, said path with its associated shield acting to transmit without excessive attenuation the band of frequencies so applied.

2. A transmission circuit comprising two cylindrical conductors of substantially the same size arranged side by side and spaced apart, a cylindrical conducting shield surrounding said conductors, one of said conductors being connected as a return for the other to form a high frequency transmission path shielded by said shield, said conductors and shield being insulated from one another by a substantially gaseous dielectric, each of said conductors consisting of a plurality of conducting strands insulated from one another and so stranded that current distribution is substantially uniform for a range of frequencies extending to a region well above audibility, the transmission path formed from said cylindrical conductors acting one as a return for the other having connected thereto apparatus for supplying thereto and receiving and utilizing therefrom a band of signal frequencies extending from approximately zero to a frequency many times the upper limit of the audible range, said path with its associated shield acting to transmit without excessive attenuation the band of frequencies so applied.

3. A transmission circuit comprising two cylindrical conductors of substantially the same size arranged side by side and spaced apart, each of said conductors consisting of a plurality of conducting strands insulated from one another and so stranded that current distribution is substantially uniform for a range of frequencies extending to a region well above audibility, a cylindrical conducting shield of predetermined diameter surrounding said conductors, one of said conductors being connected as a return for the other, said conductors and shield being insulated from one another, the relative dimensions of said conductors and shield and their relative spacing being such that the high frequency attenuation of the circuit will be a minimum for any frequency where the ratio of the resistance of either of said conductors to the resistance at the said frequency of a solid conductor of the same material and size is less than unity.

4. A transmission circuit comprising two cylindrical conductors of substantially the same size arranged side by side and spaced apart, each of said conductors consisting of a plurality of conducting strands insulated from one another and so stranded that current distribution is substantially uniform for a range of frequencies extending to a region well above audibility, and a cylindrical conducting shield of predetermined diameter surrounding said conductors, one of said conductors being connected as a return for the other, said conductors and shield being insulated from one another by a substantially gaseous dielectric, the relative dimensions of said conductors and shield and their spacings being such that the high frequency attenuation of the circuit will be a minimum at any frequency for which the ratio of the resistance of either of said

conductors to the resistance at the same frequency of a solid conductor of the same material and size lies between the limits unity and 0.4.

5. A transmission circuit comprising two cylindrical conductors of substantially the same size arranged side by side and spaced apart, each of said conductors consisting of a plurality of conducting strands insulated from one another and so stranded that current distribution is substantially uniform for a range of frequencies extending to a region well above audibility, and a cylindrical conducting shield of predetermined diameter surrounding said conductors, one of said conductors being connected as a return for the other, said conductors and shield being insulated from one another by a substantially non-gaseous dielectric, the relative dimensions of said conductors and shield and their relative spacings being such that the high frequency attenuation of the circuit will be a minimum for the frequency for which the ratio of the resistance of either of said conductors to the resistance at the same frequency of a solid conductor of the same material and size is substantially a minimum.

6. A transmission circuit comprising two cylindrical conductors of substantially the same size arranged side by side and spaced apart, each of said conductors consisting of a plurality of conducting strands insulated from one another and so stranded that current distribution is substantially uniform for a range of frequencies extending to a region well above audibility, and a cylindrical conducting shield of predetermined diameter surrounding said conductors, said conductors being helically twisted around the axis of said shield, one of said conductors being connected as a return for the other, said conductors and shield being insulated from one another, the relative dimensions of the said conductors and shield and their relative spacings being such that the high frequency attenuation of the circuit will be a minimum at any frequency for which the ratio of the resistance of either of said conductors to the resistance at the same frequency of a solid conductor of the same material and size lies between the limits unity and 0.4.

7. A transmission circuit comprising two cylindrical conductors of substantially the same size arranged side by side and spaced apart, each of said conductors consisting of a plurality of conducting strands insulated from one another and so stranded that current distribution is substantially uniform for a range of frequencies extending to a region well above audibility, and a cylindrical conducting shield of predetermined diameter surrounding said conductors, said conductors being transposed about the axis of the shield, one of said conductors being connected as a return for the other, said conductors and shield being insulated from one another, the relative dimensions of said conductors and shield and their relative spacings being such that the high frequency attenuation of the circuit will be a minimum for the frequency for which the ratio of the resistance of either of said conductors to the resistance at the same frequency of a solid conductor of the same material and size is substantially a minimum.

8. A transmission circuit comprising two cylindrical conductors of substantially the same size arranged side by side and spaced apart, a cylindrical conducting shield of predetermined diameter surrounding said conductors, one of said conductors being connected as a return for the other, said conductors and shield being insulated from

one another, each of said conductors consisting of a plurality of conducting strands insulated from one another and so stranded that current distribution is substantially uniform for a range of frequencies extending to a region well above audibility, the particular arrangement of said strands being such as to produce at a given high frequency a predetermined value for the ratio of the resistance of each of said conductors to the resistance of a solid conductor of equivalent diameter, the relative dimension of said conductors and shield and their relative spacings being such that the high frequency attenuation of the circuit will be a minimum at said given high frequency.

9. A transmission circuit comprising two conductors, a cylindrical conducting shield surrounding said conductors, one of said conductors being connected as a return for the other, said conductors and shield being insulated from one another, each of said conductors consisting of a plurality of conducting strands insulated one from another, the ratio of the interaxial separation of said conductors to the inner diameter of said shield being approximately .40 and the ratio of the inner diameter of said shield to the diameter of each of said conductors being approximately 5.0.

10. A transmission circuit comprising two conductors, each of said conductors consisting of a plurality of conducting strands insulated from one another, and a cylindrical conducting shield surrounding said conductors, one of said conductors being connected as a return for the other, said conductors and shield being insulated from one another by a substantially gaseous dielectric, the ratio of the interaxial separation of said conductors to the inner diameter of said shield being approximately .40 and the ratio of the inner diameter of said shield to the diameter of each of said conductors being approximately 5.0.

11. A transmission circuit comprising two conductors, each of said conductors consisting of a plurality of conducting strands insulated from one another, and a cylindrical conducting shield surrounding said conductors, one of said conductors being connected as a return for the other, said conductor and shield being insulated from one another by a substantially non-gaseous dielectric, the ratio of the interaxial spacing of said conductors to the inner diameter of said shield being approximately .40, and the ratio of the inner diameter of said shield to the diameter of each of said conductors being given approximately by the expression:

$$5 + 6\sqrt{F\lambda pc}(1.1 - n)$$

where n is the ratio of the resistance of each of said conductors to the resistance of a solid conductor of the same diameter at the frequency F , F is the frequency in cycles per second, λ the conductivity in abmho per centimeter cube, p the power factor, and c is the inner radius of the shield in centimeters.

12. A transmission circuit comprising two cylindrical conductors of substantially the same size arranged side by side and spaced apart, each of said conductors consisting of a plurality of conducting strands insulated from one another and so stranded that current distribution is substantially uniform for a range of frequencies extending to a region well above audibility, and a

cylindrical conducting shield of predetermined diameter surrounding said conductors, one of said conductors being connected as a return for the other, said conductors and shield being insulated from one another, the relative dimensions of said conductors and shield and their spacing being such that the high frequency characteristic impedance of the circuit derived from said stranded conductors will approximate 143 ohms for the usual value of n .

13. A transmission circuit comprising two cylindrical conductors of substantially the same size arranged side by side and spaced apart, each of said conductors consisting of a plurality of conducting strands insulated from one another and so stranded that current distribution is substantially uniform for a range of frequencies extending to a region well above audibility, and a cylindrical conducting shield of predetermined diameter surrounding said conductors, one of said conductors being connected as a return for the other, said conductors and shield being insulated from one another by a substantially gaseous dielectric, the relative dimensions of said conductors and shield and their spacing being such that the high frequency characteristic impedance of the circuit derived from said stranded conductors will approximate 143 ohms for the usual value of n .

14. A transmission circuit comprising two conductors, each of said conductors consisting of a plurality of conducting strands insulated from one another, and a cylindrical conducting shield surrounding said conductors, one of said conductors being connected as a return for the other, said conductors and shield being insulated from one another, the ratio of the interaxial separation of said conductors to the inner diameter of said shield being approximately .486.

15. A transmission circuit comprising two cylindrical conductors of substantially the same size, the interaxial separation of said conductors being greater than the diameters, a cylindrical conducting shield of predetermined diameter surrounding said conductors and substantially concentric with a line midway between the centers of the two said conductors, one of said conductors being connected as a return for the other to form a high frequency transmission path shielded by said shield, said conductors and shield being insulated from one another, each of said conductors consisting of a plurality of conducting strands insulated from one another and so stranded that current distribution is substantially uniform for a range of frequencies extending to a region well above audibility, the transmission path formed from said cylindrical conductors acting one as a return for the other having connected thereto apparatus for applying thereto and receiving and utilizing therefrom a band of signal frequencies extending from approximately zero to a frequency many times the upper limit of the audible range, said path with its associated shield acting to transmit without excessive attenuation a band of frequencies so applied, the relative dimensions of said conductors and shield and their relative spacings being such that the high frequency attenuation of the circuit will be a minimum at the highest frequency of said band of signal frequencies.

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