

Aug. 16, 1932.

H. NYQUIST

1,871,906

CONCENTRIC SHIELD FOR CABLES

Filed July 20, 1929

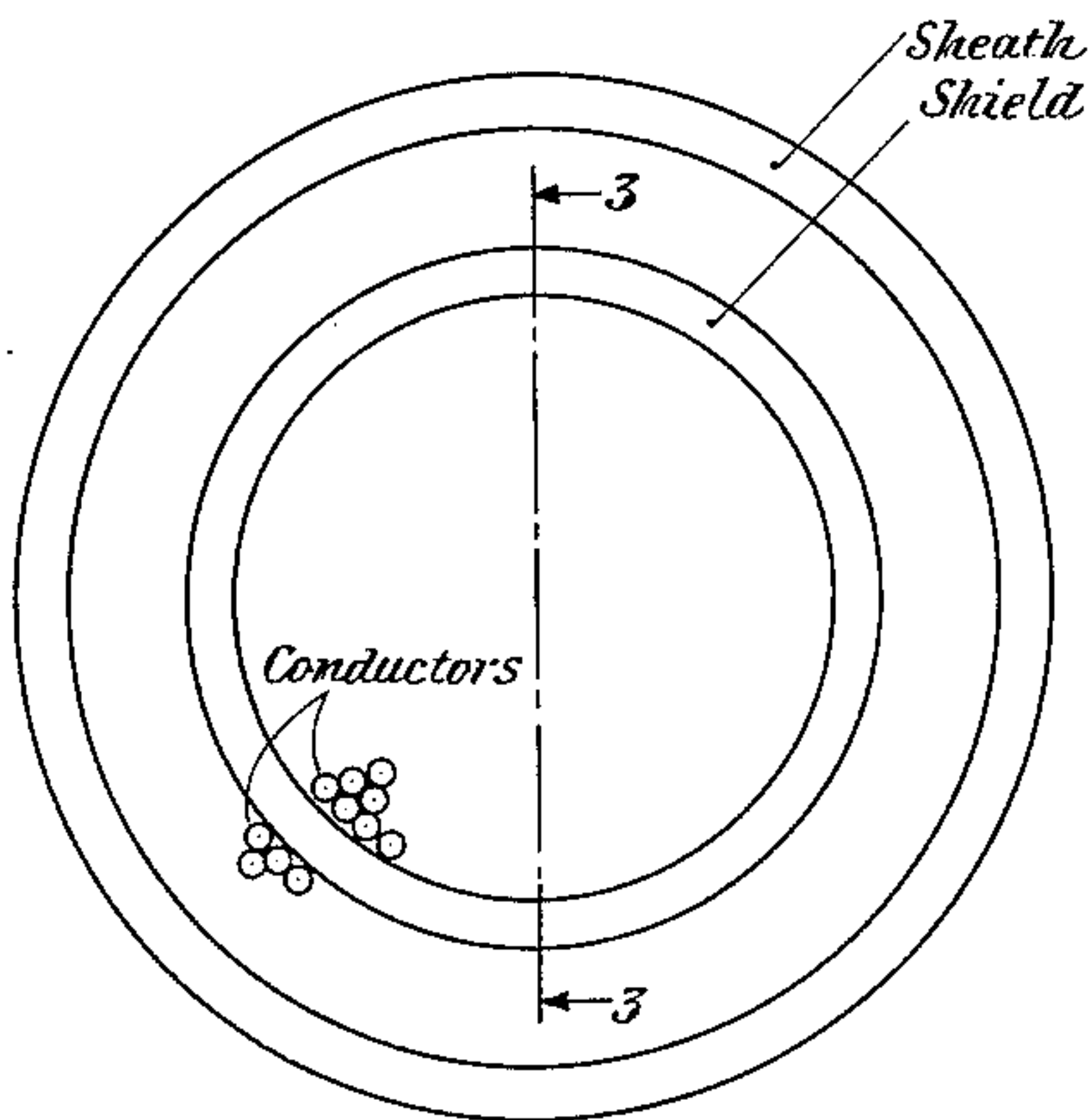


Fig. 1

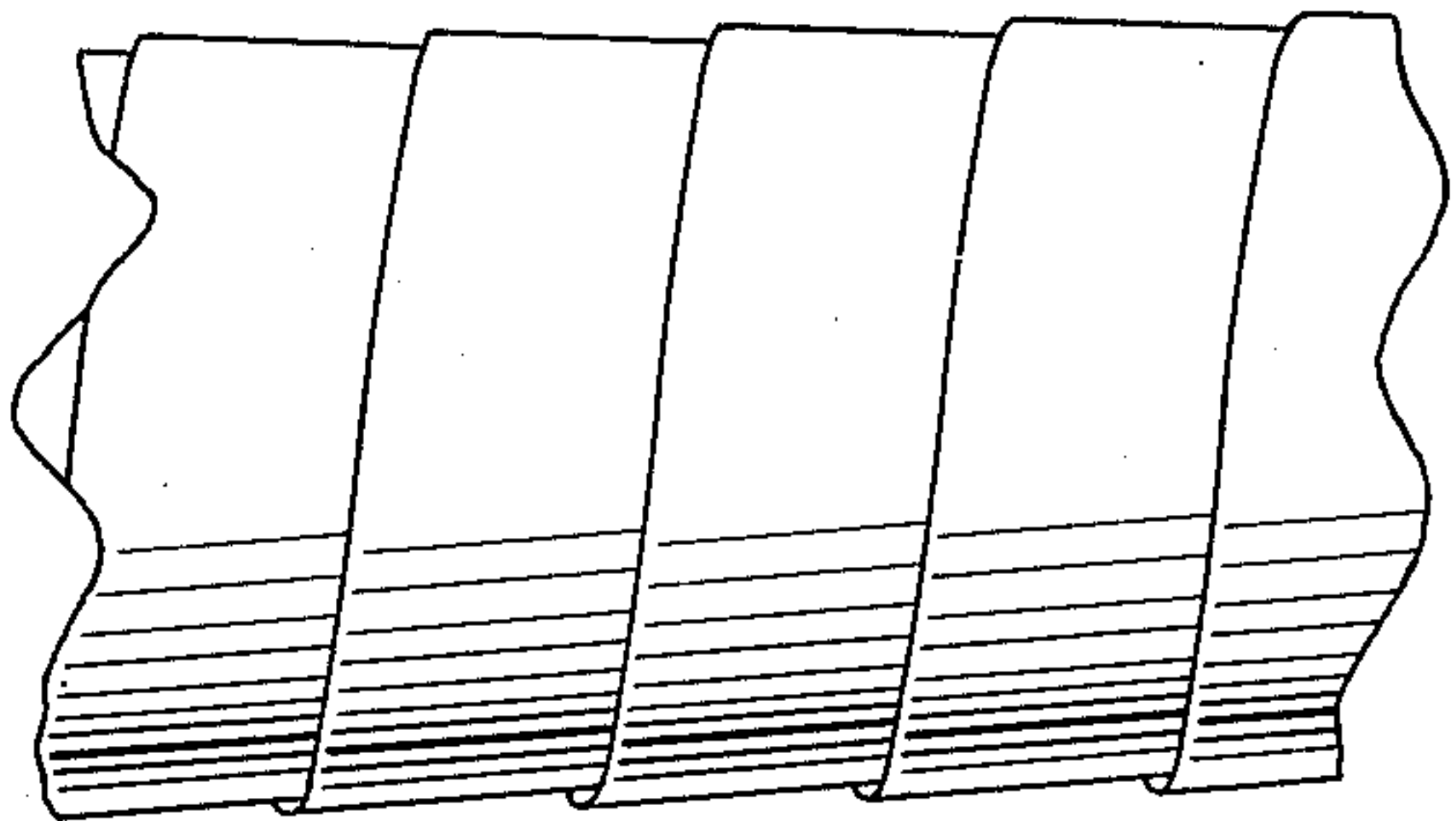


Fig. 2

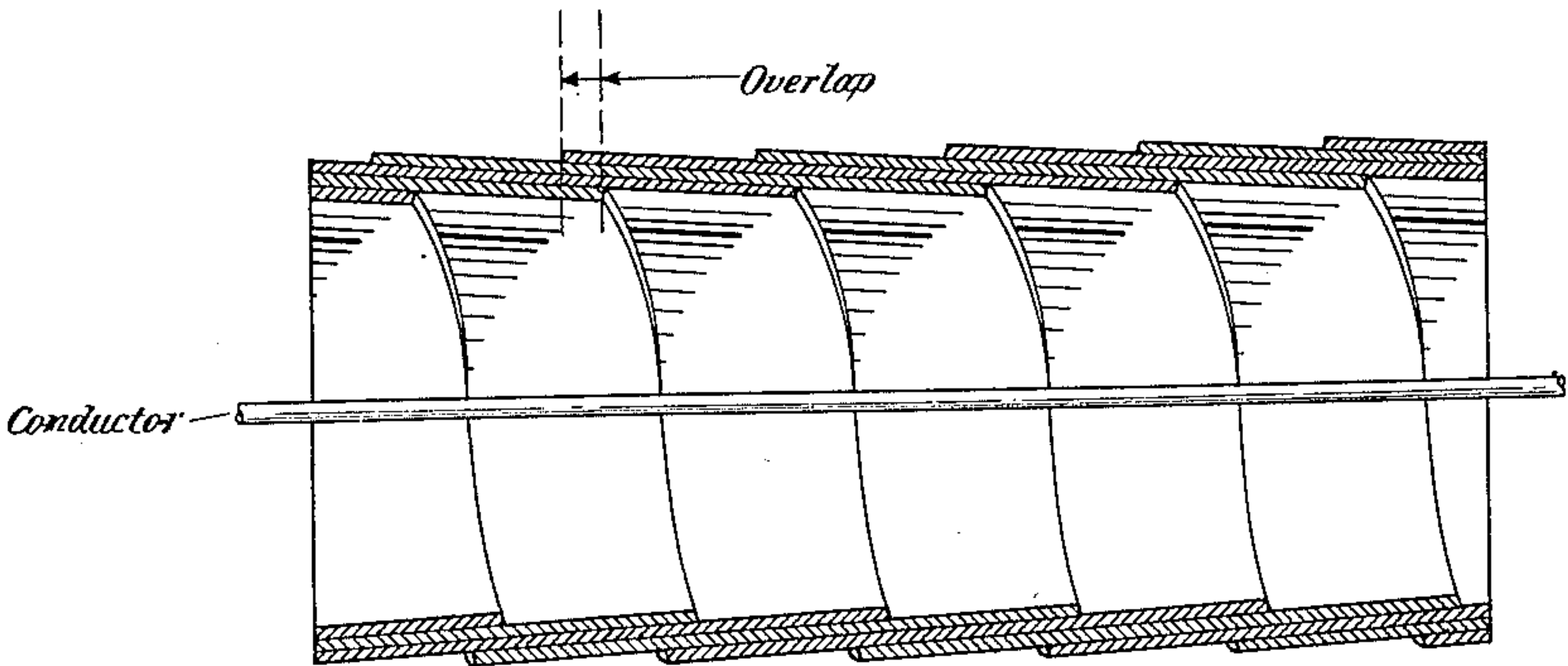


Fig. 3

INVENTOR
H. Nyquist
BY *Elmer C. Rose*
ATTORNEY

UNITED STATES PATENT OFFICE

HARRY NYQUIST, OF MILLBURN, NEW JERSEY, ASSIGNOR TO AMERICAN TELEPHONE
AND TELEGRAPH COMPANY, A CORPORATION OF NEW YORK

CONCENTRIC SHIELD FOR CABLES

Application filed July 20, 1929. Serial No. 379,842.

This invention relates to multi-conductor cables and has particular reference to arrangements for shielding certain of the conductors of such a cable from other conductors of the cable.

In order to transmit currents of the same frequency in both directions within the same cable, and more particularly when the currents to be transmitted are carrier frequencies, it is desirable that the conductors used for transmitting in one direction be shielded from those transmitting in the opposite direction. Accordingly, it is proposed to arrange the conductors of a cable in two concentric groups with a concentric shield, preferably of soft iron, between the two groups of conductors. In such an arrangement of the cable those conductors within the shield may all be used for transmitting carrier frequencies in one direction while the return channels for transmission in the opposite direction will be applied to the conductors in the other concentric group. The shield has the effect of reducing so-called "near end" crosstalk since the weak attenuated currents coming in at a repeater point are in a compartment of the cable shielded from the large amplified currents entering the conductors in the other compartment of the cable.

Preferably, the cable with the concentric shield is formed by arranging a group of conductors into a cylindrical bundle, spirally wrapping a very wide and thin tape of soft iron or other suitable material upon the cylindrical bundle of wires, and then mounting another group of wires, preferably equal in number, outside of the shielding tape in the form of a concentric cylindrical bundle upon which the outer shield of lead or other material is applied in the usual manner. In wrapping the tape the ribbon should be several times as wide as the pitch of the spiral in accordance with which the tape is wound, and the tape should be relatively thin so that several layers of the shielding material overlap each other in such a way that the laminations approach a condition of parallelism with the surface of the shield. While various materials may be used iron, and particularly soft iron, are preferred because the product

of the permeability by the conductivity of the iron is large, thereby making its attenuating effect large, and furthermore, the ratio of the permeability of the iron to its conductivity is quite different from that of the copper or other conductive material used for the conductors, with the result that the reflection losses through the shield are large.

The invention will now be more fully understood from the following description, when read in connection with the accompanying drawing, Figure 1 of which is a transverse cross-section showing the relative positions of the sheath, the intermediate shield, and two groups of conductors (for simplicity only a few of the conductors are actually shown); Fig. 2 is a side view of the shield showing how it is spirally wrapped; and Fig. 3 is a longitudinal section along the lines 3—3 of Fig. 1, showing how the thin wide layers of the shield overlap each other.

In order to design a proper shield for the purposes above set forth, and in order to give proper weight to the merits of different types of shields, it is desirable to have available a quantitative theory to give at least the first approximation of the shielding effects.

In case of low frequencies, the calculations of the shielding effects are simplified by the assumption that the currents in the shield distribute themselves uniformly and in phase. In the case of the higher carrier frequencies with which we are now concerned, this assumption is no longer permissible unless the shields are very thin. It is necessary to recognize that the energy is propagated through the shield in the form of electromagnetic waves which are propagated with a finite velocity. The differential equations for such electromagnetic waves are known accurately but the labor of integrating them in their accurate form is prohibitive. In the following discussion an approximate theory will be outlined which it is thought will be amply accurate for practical purposes.

The cable to be considered herein is made up of the usual cylindrical lead sheath within which the conductors are arranged in the usual fashion except that they are separated into two equal or substantially equal separate

concentric groups by means of a cylindrical concentric shield. When a signal is transmitted over any circuit in this cable, it is permissible to consider an electromagnetic field as spreading out from this circuit in the form of a wave motion. This wave reaches other conductors and may induce currents and electromotive forces in other circuits unless they are perfectly balanced. The first of these circuits may be called the disturbing circuit and the other the disturbed. If the disturbing and disturbed circuits are on opposite sides of the shield, it is obvious that the disturbance is reduced due to the attenuation in the shield.

The electromagnetic condition of a cable is given by specifying the electric and magnetic field both as to magnitude and direction at every point and at every instant. The problem will be greatly simplified by confining attention to one frequency component of these fields, that is to say, one of the components obtained by making a Fourier analysis of the fields over a sufficiently long time. It will be understood that this analysis is carried out at every point and relates to the directional components of the fields as well as to their magnitude. Having thus separated out one frequency component, the electric and magnetic vectors at any given point may have any one of several relations which will be discussed briefly in turn.

In the following discussion E is the electric, H is the magnetic field, C the current density, μ the permeability, σ the conductance and c is ratio of the electromagnetic unit of current to the electrostatic unit of current, or conversely it is the ratio of the electrostatic unit of EMF to the electromagnetic unit of EMF. These quantities are to be measured in electromagnetic units.

The postulates stated below under a to f , inclusive, are not quantitatively exact unless further restrictions are imposed which would complicate the picture. These statements are not used in a quantitative sense in what follows, however. Their function is to fix a physical picture in the reader's mind to permit a better understanding of the subsequent discussions.

a. Electric field in phase with and perpendicular to the magnetic, and energies of two fields being equal. ($E=cH$).

Under the assumed conditions of equality, phase and direction of the fields, the total energy of the fields is propagated in a third direction which is perpendicular to both fields.

b. The fields in phase and perpendicular to each other but unequal in magnitude. $E \geq cH$

It is convenient to begin with a case where one of the fields, say H , is zero. In that case

it is permissible to introduce two fictitious magnetic fields equal in magnitude and opposite in direction, each of them being equal to

$$\frac{H}{2} = \frac{E}{2c}$$

and to associate each one of these magnetic fields with one-half of the electric field. It is seen that the result is two energy trains transmitted in opposite directions. In the case where H is equal to neither zero nor E/c , two energy trains may be deduced in similar manner although they will not be equal.

c. Fields in phase and parallel

In this case it is possible to introduce fictitious fields of both kinds in such a way as to obtain two pairs of fields such that H equals E/c for each pair but having different relative directions. We, therefore, have two energy trains traveling in opposite directions.

d. The fields in phase but inclined at an oblique angle to each other

In this case again it is possible to introduce fictitious fields and to obtain two wave trains traveling in opposite directions which directions are perpendicular to those of the fields.

e. Fields 90° out of phase

In this case it is possible to treat each component as if the other field were not present as indicated under b above. In other words, each field gives rise to two equal waves traveling in opposite directions.

f. Two fields are out of phase by an angle other than 90°

In this case it is possible to resolve either one of the fields into two components one of which is in phase with the other field and the other at right angles. This again gives rise to waves such as indicated under b and e above.

The possibilities a to f , inclusive, include all the possible relationships of electric and magnetic vectors with respect to phase and direction. It is seen that in all cases where two vectors coexist, the direction of propagation is at right angles to the plane containing both of them.

Coming now to the specific problem of shielding, it will be convenient to limit consideration to those waves which travel at right angles to the shield, that is to say, to those waves whose magnetic and electric fields are both parallel to the surface of the shield. These waves travel either directly toward or directly away from the shield. If they travel toward the shield, they suffer partial reflection at the surface which will be more fully discussed below. The portion which is not reflected is propagated through the shield and as it emerges at the other end it again suffers

a partial reflection and the portion which is not reflected is transmitted into the compartment at the other side of the shield. The important thing is how much weaker the emerging beam is than the incident. The most important contributing factor is the attenuation and this will be discussed first, the matter of reflection being referred for the time being.

7. Attenuation of perpendicular wave in a plane metallic conductor

While the shield is actually cylindrical, it will be permissible to consider a plane shield of the same thickness, as the error involved is very small unless the inner diameter of the shield is small in comparison with the outer one. It will be assumed that the shield is homogeneous and of uniform thickness.

For the time being, it will also be assumed that the waves are plane, polarized and infinite in extent. Inside of the conductor comprising the shield we are interested in two vectors in addition to the two fields, namely, the flux density $B = \mu H$ and the current density $C = \sigma E$. (The displacement current may be neglected in comparison with the conduction current; in other words, the capacity of a cubic centimeter of the material may be neglected in comparison with its conductance.)

The manner in which the waves are propagated inside of the shield is determined by two well-known physical laws: (1) the law that the cutting of magnetic lines of force produces an electric field; and (2) the law that a current produces a magnetic field.

The mathematical expression for the first law in the form of a differential equation is, (where t represents time),

$$-dB/dt = \text{curl } E \quad (1)$$

This equation represents the case where components of the field are propagated along three axes of a coordinate system. In the case we are considering of a plane wave plane polarized, this expression can be much simplified because the propagation is along a single axis. Let z be the direction of propagation, x the direction of the electric field and y the direction of the magnetic field. Then Equation (1) reduces to

$$-dB_y/dt = dE_x/dz \quad (1a)$$

The subscripts y and x applied to B and E indicate the axes of the respective fields.

The second law referred to above according to which current produces a magnetic field, is given by the expression

$$4\pi C = \text{curl } H \quad (2)$$

which, in the case of the wave we are considering, reduces to

$$4\pi C_x = -dH_y/dz \quad (2a)$$

Substituting the values μH and σE for B and C , respectively, in Equations (1a) and (2a) they become

$$-\mu dH_y/dt = dE_x/dz \quad (1b) \quad 70$$

and

$$4\pi\sigma E_x = -dH_y/dz \quad (2b)$$

If E_x is eliminated between these equations by differentiation of Equation (2b) with respect to z and substituting, we have

$$4\pi\sigma\mu dH_y/dt = d^2H_y/dz^2 \quad (3) \quad 75$$

Likewise, eliminating H_y by differentiating Equation (1b) with respect to z and Equation (2b) with respect to t , we have

$$4\pi\sigma\mu dE_x/dt = d^2E_x/dz^2 \quad (4) \quad 80$$

The law of propagation of H_y expressed in (3) is the same as the law of propagation of E_x expressed in (4).

It may be shown that Equation (3) is equivalent to

$$H_y = Me^{+i\omega t} e^{-Pz} \quad (3a) \quad 90$$

where M is a constant, ω is 2π times the frequency and P , the propagation constant, is given by the expression

$$P = \alpha + i\beta = \sqrt{i4\pi\omega\sigma\mu} \quad (5) \quad 95$$

from which it follows, if σ and μ are both real, that

$$\alpha = \beta = \sqrt{2\pi\omega\sigma\mu} \quad (5a)$$

α and β being the attenuation constant and the wave constant, respectively.

Similarly it may be shown that Equation (4) is equivalent to

$$E_x = Ne^{+i\omega t} e^{-Pz} \quad (4a) \quad 105$$

where N is also a constant and the other quantities have the same values as in Equation (3a).

In evaluating the expression for the attenuation constant α as given in Equation (5a), it should be remembered that the quantities are in electromagnetic units. For the permeability μ the ordinary numerical value which makes the permeability of air unity may be used. For the conductivity σ it is necessary to take the numerical value as expressed in mhos per cm^3 (this means the conductance of a cube one centimeter each way) and multiply them by 10^{-9} . With these values substituted, the attenuation will be given in nepers per cm. In order to express the attenuation in decibels (db.) per inch, the attenuation constant obtained should be further multiplied by 8.69, the ratio of the neper to the decibel, and by 2.54, the ratio of the inch to the centimeter. The result thus obtained for copper is $3.3\sqrt{f}$ db. per inch, where f is expressed in cycles per second. For lead, the corresponding attenuation is approximately $\sqrt{f}$.

In the case of iron, the computation is complicated by the fact that the permeability is not real, that is to say, there is a hysteresis loop. It will be sufficient, in order to obtain a first approximation to the effect of hysteresis, to assume that the hysteresis loop is in the form of an ellipse, inclined to the axes in a similar manner to the hysteresis loop. Just as we say that the electrical admittance of a network having this kind of loop is a complex quantity $R + ix$, so we may say in the present case that $\mu = m - in$, where m and n are positive real quantities. The quantity m is obtained by dividing the value of B , corresponding to the maximum value of H on the equivalent ellipse, by the maximum value of H ; and n is obtained by dividing the value of B , corresponding to $H = 0$, by the maximum value of H . It is clear from a comparison of the expression $\mu = m - in$ with Formula (5) that the effect of hysteresis is to increase the attenuation α due to the component m of the permeability, and decrease the wave constant β due to the effect of the component n of the permeability; in other words, to increase both the attenuation and the velocity.

Assuming that n may be neglected and that an iron is available having a conductivity one-sixth that of copper and a permeability of 600, the attenuation would be ten times that of copper or $33\sqrt{f}$ db. per inch.

2. Oblique incidence

We are still dealing with a large plane shield, and a plane and plane polarized wave, but the wave is propagated in a direction which is not perpendicular to the plane of the shield in the air. The direction of propagation within the shield is, however, substantially perpendicular to the plane of the shield. Upon entering the shield, the direction of the wave is altered; this follows from the fact that the velocity is very much less in the conductor than in the air. In the case of a wave of frequency of 40 kc., the velocity in copper is 8.4×10^3 cm. per second, whereas its velocity in air is 3×10^{10} cm. per second. In other words, the velocity in air is about 3.6×10^6 times as great as in the metal. It will be obvious that a wave striking the metal even at a considerable angle to the normal will travel substantially parallel to the normal inside the metal. For this reason the attenuation of the wave is substantially the same regardless of whether the incidence of the wave is normal or oblique.

3. Cylindrical shield

Here it is convenient to introduce the principle known as Huygens' construction. In accordance with this construction the wave at any interior point of the shield can be looked upon as the resultant of a large number of small waves. At each point of the surface of the shield, we may consider that a

small hemispherical wave is set up and spreads equally in all directions. When all these spherical wavelets are summed up at any interior point of a plane shield, values of H_y and E_x are obtained which are equal to those given in Equations (3a) and (4a). This method of construction will also enable us to estimate the effect of a cylindrical shield. If the waves are traveling outward through the shield, the spherical waves that reach the outer surface do not reinforce one another to the same extent that they would if the shield were plane. In other words, the wave traveling outward is diminished slightly more than it would be in a plane shield. If the wave is traveling inward the opposite is true. This effect, however, which is an effect of spreading of the energy in the case of outgoing waves and a concentration in the case of incoming waves, exists whether the shield is present or not, and since we are particularly interested in the increase in attenuation which the shields produce, it will be permissible to use the figure obtained for a plane shield.

4. Reflection in infinite space

The space is assumed infinite in order to avoid consideration of multiple reflections which are bound to occur in any practical case. Moreover, both the wave and the shield are assumed to be plane and parallel to each other and the wave is plane polarized.

First consider the case of the reflection phenomena accompanying the incidence of the wave on the metal. Let the electric field in the incident wave be E_{xi} . Likewise let the electric field in the reflected wave be E_{xr} and in the transmitted wave E_{xt} . Let H_{yi} , H_{yr} and H_{yt} be the corresponding magnetic fields. These fields are continuous in going from one medium to another and we have, therefore,

$$E_{xi} + E_{xr} = E_{xt} \quad (6) \quad 110$$

$$H_{yi} + H_{yr} = H_{yt} \quad (7)$$

From Equations (2a) and (5) we have, designating the electric field within the conductor E_{xt} and the magnetic field within the conductor H_{yt} ,

$$4\pi\sigma E_{xt} = PH_{yt} \quad (8)$$

The equations corresponding to (2a) and (1a) in air are

$$(1/c^2) dE_x/dt = -dH_y/dz \quad (9)$$

$$-dH_y/dt = dE_x/dz \quad (10)$$

leading to the expressions

$$E_{xi} = cH_{yi}, \text{ and } (9a)$$

$$E_{xr} = -cH_{yr} \quad (10a)$$

Substituting for the E's in (6) the values

given in (8), (9a) and (10a), Equation (6) becomes

$$cH_{yt} - cH_{yr} = \sqrt{i\omega\mu/4\pi\sigma} H_{yt} \quad (6a)$$

5 Solving the simultaneous Equations (6a) and (7) in terms of H_{yt} and H_{yr} , respectively, we get

$$H_{yt} = \{2c/(c + \sqrt{i\omega\mu/4\pi\sigma})\} H_{yt} \quad (11)$$

$$10 H_{yr} = \{(c - \sqrt{i\omega\mu/4\pi\sigma})/(c + \sqrt{i\omega\mu/4\pi\sigma})\} H_{yt} \quad (12)$$

Substituting in (11) and (12) the expression for H's in terms of the E's given in (8), (9a) and (10a)

$$15 E_{xt} = -\{(c - \sqrt{i\omega\mu/4\pi\sigma})/(c + \sqrt{i\omega\mu/4\pi\sigma})\} E_{xt} \quad (12a)$$

$$E_{xt} = \{2\sqrt{i\omega\mu/4\pi\sigma}/(c + \sqrt{i\omega\mu/4\pi\sigma})\} E_{xt} \quad (11a)$$

20 To state the foregoing in words, since the term

$$\sqrt{i\omega\mu/4\pi\sigma}$$

is small, Equations (12) and (12a) mean
25 that the reflected wave is substantially equal to the incident wave; Equation (11) indicates that the entering wave has substantially twice the magnetic fields of the incident wave; and Equation (11a) shows that the
30 entering wave has its electric field multiplied by the small factor

$$\sqrt{i\omega\mu/4\pi\sigma}/c \text{ (about).}$$

In copper this fraction is about 4×10^{-7} at
35 40 kc.

These are the relations for the wave entering the conductor. On leaving the conductor there is a similar reflection phenomenon. It will be seen that the expression for the re-
40 flected and transmitted wave are obtained from (11), (11a), (12) and (12a) by interchanging the two quantities c and

$$\sqrt{i\omega\mu/4\pi\sigma}.$$

45 In particular it will be seen that the electric field is multiplied by 2 and the magnetic field by 4×10^{-7} . The net result of the two reflections is to multiply both the electric and the magnetic fields by 8×10^{-7} , which
50 corresponds to a reflection loss of about 120 db. for the combined effect of entering and leaving a copper shield.

5. Multiplicity of surfaces

55 From the result just obtained it would at first appear that reflections play an important part in reducing the intensity of the wave. It might even be thought that the artificial production of reflections obtained by separating successive shields by an air space would be beneficial. This, however, is not the case.

60 Consider the situation where two shields are separated by a distance of one cm. The wave strikes the first shield and is in large measure reflected and in part transmitted.

The transmitted wave penetrates the shield with attenuation and at the opposite surface of the shield is in part reflected and in part transmitted into the air space. The reflected wave travels very slowly back through
70 the metal and may be left for the moment while we follow the wave which is transmitted. Consider its electric field, (E_x). If the electric field of the incident wave (at this second reflection) be assumed to have a value 1, the value of the reflected wave is also
75 about 1 and that of the transmitted wave about 2. The transmitted wave crosses the one cm. air space between the shields without attenuation and with very little phase
80 shift. When it strikes the second shield it is in part reflected and in part transmitted. The reflected wave is almost as great as the incident but not quite, having lost a small fraction which goes into the transmitted
85 wave. The reflected wave returns to the first shield where its electric field is again diminished by a small amount; however, the main portion is reflected to the second shield again. Thus there is a large number of suc-
90 cessive reflections and at each reflection the wave gives up a portion of its electric field to one or the other of the shields. Due to the small phase shift involved these increments in electric field transmitted to the
95 shields add substantially in phase. Now the original value of the wave transmitted through the air is 2. The two waves built up in the two conductors as a result of the multiple reflections are each of magnitude
100 one. In other words each is equal to the incident wave before emerging from the first shield. The wave thus built up in the second shield is therefore of the same strength as it would have been if there had been no
105 air gap.

Now consider the wave of value 1 built up in the first shield. This is the result of the odd numbered reflections and therefore the electric field is reversed in phase. Before
110 this wave proceeds back into the first shield it combines with the original reflected wave (of value 1) which we previously left being slowly propagated back through the first shield. As both waves are substantially
115 equal the net result by way of a wave returned into the first shield is substantially zero. It will be apparent then that the air space is of substantially no effect.

120 If, however, the intervening space had caused considerable phase shift or if it had produced even a relatively small amount of attenuation, its effect would have been appreciable. In particular it would seem
125 that if two different metals having different ratios μ/σ are used for making up the shield, they should be alternated in relatively thin layers to take advantage of the reflections at their adjoining surfaces. The significance
130 of the ratio μ/σ is clear from Equations (11),

(11a), (12), and (12a) which show that the relative values of the transmitted and reflected waves are functions of $i\omega \mu/4\pi \sigma$ and hence of the ratio of permeability μ to conductivity σ .

From the foregoing consideration of the effect of multiple reflections, it would appear that the reflection losses which would occur at the first reflection from a single shield in an infinite space would not be effective, where the space is finite and the shield and the conductor are made of the same material, owing to the multiple reflections between the conductor and the shield. In other words, the only loss which is useful in such a case is the attenuation loss in the shields.

6. Reflection at oblique incidence

The computation of the reflection coefficient at oblique incidence is more difficult than the corresponding computations for normal incidence as given under heading 4. Moreover it turned out (see Heading 5) that when the reflection coefficients had been found for the case of normal incidence they had no appreciable bearing on the effect produced by the shield. It may, therefore, be reasonably questioned whether it is worth while to carry out the computations for the case of oblique incidence. In any event it can be seen from physical considerations that the reflection coefficients and reflection losses do not differ in kind but merely in degree from those obtained for normal incidence. This being the case the same general arguments as were used above can be employed to show that the reflections at two surfaces separated by an air space are substantially cancelled out in the case of oblique incidence, as well as in the case of normal incidence. Similarly it may be concluded that when the disturbing and disturbed circuits are separated by relatively short distances the reflection from even a single shield does not enter materially into the ultimate effect.

7. Longitudinal disturbances versus local eddies

It has been assumed above in dealing with plane shields that the waves were infinite in extent and that the intensity at any point of the shield surface was equal to that at any other point. It has also been indicated that the results obtained in this way apply to a very close approximation to the case of cylindrical surfaces if the intensity is the same at all points of the surface. It is of interest to inquire to what extent the results apply to actual field distributions. The actual distribution may differ from the ideal one just discussed in two respects. In the first place the fields may be uniform along a line drawn around the cable as above but may vary along the cable. Secondly, the field may vary on a

line around the cable as well as along the cable.

If the field does not vary appreciably on a line around the cable the disturbance is said to be longitudinal. The longitudinal disturbance is usually the one of greatest importance if the disturbed and disturbing circuits are separated by great distances. This need not be the case, however, when it is a question of crosstalk between circuits in the same cable since the separation between disturbing and disturbed circuits is relatively small. In the case of crosstalk there is a certain field set up which is determined largely by the relative position of the two wires. Now if we compare two positions along the cable which are separated by the distance of one-half twist in the pair, it is obvious that the relative position of the two conductors is interchanged and, therefore, if it may be assumed that the current and voltage are the same at the two points, the fields set up will be just opposite. It is also obvious that if the pair is nearer one side of the cylinder than another, the field at the surface of the cylinder will be a function of position. For both of these reasons it may be concluded that the fields consist in part at least of local eddies rather than longitudinal disturbances.

Regardless of how complicated a function of position on the surface of the shield the field may be, it is possible to analyze it by means of a double Fourier series into components. This is entirely similar to the manner in which a picture in telephotography may be analyzed into a double Fourier series. Let us assume that such an analysis has been carried out for, say, the electric field just inside the surface of the shield and let us confine attention to one of the components thus found. In comparing the manner in which this component is propagated in comparison with the uniform wave assumed above it will be convenient to make use of Huygens' construction. In accordance with this construction the wave inside of the shield may be considered as the resultant of a large number of hemispherical waves, each one starting at a point of the surface. If these waves are all equal, as they are in the case of the uniform plane wave, the laws deduced above hold. If there is a considerable difference from point to point of the surface it will be seen by following these hemispherical waves that there is a tendency to equalize differences. However, unless the field on the surface changes materially in a distance equal to the thickness of the shield, the equalizing effect will be very small. If on the other hand the field varies very rapidly over the surface of the conductor, so that there is a great variation in proceeding a distance equal to the thickness of the shield, the result is that some components of the wave mutually annihilate each other and thereby produce

a greater shielding effect than in the case of a uniformly distributed field as previously deduced. It is thought that in all cases of practical interest the variation over the surface is relatively slow and that therefore the results obtained from the uniform waves apply without modification.

8. Seams and laminations in shields

The shield may be said to function because of the eddy currents and magnetic flux set up in the material. It is obvious then that if the shield contains laminations in such a direction as to break up the flow of current or the magnetic flux, the effectiveness of the shield will be impaired. On the other hand there is no objection to laminations running perpendicular to the direction of flow of energy because neither current nor magnetic flux flows across such surfaces. In the case of longitudinal disturbances it is particularly important that the longitudinal current be not interrupted and that the circulating flux be not interrupted. For such disturbances parallel copper wires are just about as efficient as a solid shield containing the same amount of copper since the magnetic flux through the copper is small in any event and the parallel wires do not interrupt longitudinal currents. On the other hand a solid iron shield with a given amount of iron will be much more effective than the same amount of iron in the form of either parallel or helical wires, because the helical wires impede longitudinal currents and the parallel wires impede circulating fluxes. It seems that the best way to avoid the effect of seams and laminations is to make up the shield with fairly thin tape, as wide as can be conveniently handled, and wrapped several times. In such case the seams approach parallelism with the surface of the shield and the effect of unavoidable components of the seams transverse to the surface of the shield is to some extent neutralized by the presence of neighboring layers of metal which in effect overlap the seams.

9. Design of shield

There will now be described a shield construction suitable for separating two concentric groups of conductors within a cable. As has already been made clear, the purpose of the shield is to reduce crosstalk between circuits in the two compartments separated by the shield. The general construction of the cable and location of the shield are indicated in the figures of the accompanying drawing.

The attenuation of a solid shield is equal to the thickness times the attenuation constant α . In accordance with Equation (5a) the attenuation constant is given by the expression

$$\sqrt{2\pi\omega\sigma\mu}$$

where σ and μ are the conductivity and permeability, respectively, in electromagnetic units. In order to make the attenuation of the shield as great as possible for a given thickness, it is desirable, therefore, that the product $\mu\sigma$ be as large as possible. It is also

desirable that the quotient $\frac{\mu}{\sigma}$ for the shield differ as much as possible from the corresponding quotient for the conductors. This insures a certain reflection loss in the shield in addition to the attenuation loss, because the reflection effects between the shield and the material of the conductors do not cancel out, as has been fully discussed under headings 4 and 5. A third property which is somewhat desirable but much less important than the foregoing is that the material have considerable hysteresis loss since the hysteresis effect increases the attenuation, as already explained under heading 1. In addition to these desirable properties relating to the substance of which the shield is made, it is desirable that it be free from seams or laminations which would interrupt the flow of current or magnetic flux. Laminations parallel to the surface of the shield are not objectionable.

In comparing various substances that might be available, the question arises whether a ferromagnetic substance or a substance of high conductance is preferable. The best non-magnetic substances are copper, silver and aluminum. There is very little choice in performance among these three. Taking copper as representative and comparing it with, say, iron, it is found that the conductivity σ is decreased in the ratio of 6:1 in going from copper to iron. However, the permeability μ is increased in a very much greater ratio, possibly as much as 600:1. If we assume the latter figure the product $\sigma\mu$ is increased in the ratio of 100:1 which means that the attenuation constant α is increased in the ratio of 10:1 and the required thickness of shield is decreased in the ratio 1:10. In addition, the ratio μ/σ is very greatly increased in going from copper to iron and there is, therefore, an appreciable reflection loss.

For both of these reasons, it seems, therefore, that iron is greatly advantageous to copper. Moreover iron should be used if the shield is thick enough to make the amount of material employed of importance. Now it turns out that in the problems of interest, the thickness of the copper shield would be on the order of $\frac{1}{16}$ inch which means a great amount of copper. It, therefore, may be concluded that iron should be used.

From a mechanical standpoint it seems that the most practicable way of applying the shield is to make it in the form of a tape and wind it around the inner core of conductors. Now iron is a readily oxidized metal and it might well be that oxides would form in suffi-

cient quantity to seriously interfere with the conductivity and even the magnetic flux. It is proposed that these disadvantages be overcome by two expedients. In the first place, 5 make the tape wide and thin so that the width of the tape considerably exceeds its pitch when applied to the core. This makes the laminations approach the condition of parallelism with the axis of the cable so that they 10 do not interfere with longitudinal conductivity and magnetic flux. In the second place, coat the iron with some suitable metal which is not subject to oxidation to any great extent and which will insure good contact between 15 successive layers of the tape. It is not necessary that there be good contact over the whole surface but there should be sufficient contact so that the longitudinal resistance of the tape when in place is not greatly different from 20 that of a solid shield. It is thought that tin would be a suitable substance for this purpose, but other substances such as lead, zinc, copper, silver, gold, nickel, chromium and various amalgams may also be employed.

25 To reduce the effects of seams, in a cable of ordinary size the width of the tape should be made as great as possible, say about six inches, and preferably not less than one inch as a minimum. If we assume that the pitch is 30 so chosen that there are three thicknesses of tape at every point and if we assume that the total thickness of shield required is 15 mils, the thickness of the tape required works out to be 5 mils.

35 The figures on the drawing show the construction contemplated. Fig. 1 shows the location of the shield with respect to the remainder of the cable. Fig. 2 shows the external appearance of the shield in place. Fig. 40 3 is a longitudinal cross-section of the shield showing the inside appearance of the shield and the character of the effective lamination. In order to make the interior appearance clear, all the conductors but one have been removed from the inside in this figure. The 45 figures are for the most self-explanatory but the distance marked "overlap" in Fig. 3 calls for comment. This distance should be equal to the thickness of the tape to a first approximation. If it is made less than this there 50 will be a weak spot in the shield so far as its shielding effect is concerned. If it is made much greater than this, the material is used inefficiently.

55 It will be apparent that the shield described, forms a continuous covering from one end of the cable to the next. It is necessary, therefore, to avoid magnetization effects due to direct current flowing longitudinally of the shield. To avoid this the shield 60 should be insulated from the ground at the terminals of a repeater section so that normally there will be no direct current flowing in it. On the other hand, the material ought 65 to be such as not to be permanently magne-

tized by incidental direct current. Also, the material ought to be such that it does not approach saturation due to the earth's magnetic field. Making the shield of soft iron satisfies 70 both of these requirements.

It will be obvious that the general principles herein disclosed may be embodied in many other organizations widely different from those illustrated, without departing 75 from the spirit of the invention as defined in the following claims.

What is claimed is:

1. A cable comprising a plurality of conductors arranged in two concentric cylindrical bundles one within the other, and a concentric shield of magnetic and conductive material interposed between the bundles, said shield being in the form of a thin wide tape wound helically about the inner bundle, and the width of said tape being more than twice 85 the pitch of the helix.

2. A cable comprising a plurality of conductors arranged in two concentric cylindrical bundles one within the other, and a concentric shield of magnetic and conductive material interposed between the bundles, said shield being in the form of a thin wide tape wound helically about the inner bundle, and the width of the tape being such with respect 90 to its thickness and the pitch of the helix that the shield will comprise a plurality of layers of tape at each point along the length of the cable and the effective laminations will approach parallelism with the surface of the 95 shield.

3. A cable comprising a plurality of conductors arranged in two concentric cylindrical bundles one within the other, and a concentric shield of soft iron interposed between the bundles, said shield being in the form of 100 a thin wide tape wound helically about the inner bundle, and the width of said tape being more than twice the pitch of the helix.

4. A cable comprising a plurality of conductors arranged in two concentric cylindrical bundles one within the other, and a concentric shield of soft iron interposed between the bundles, said shield being in the form of a thin wide tape wound helically about the inner bundle, and the width of the tape being 105 such with respect to its thickness and the pitch of the helix that the shield will comprise a plurality of layers of tape at each point along the length of the cable and the effective laminations will approach parallelism with the surface of the shield. 110 115 120

5. A cable comprising a plurality of conductors divided into two substantially equal groups with certain conductors of one group arranged to transmit in one direction and certain conductors of the other group arranged to transmit in the opposite direction, the two groups being arranged in the form of two concentric cylindrical bundles one within the 125 other, and a concentric shield interposed be- 130

5 between the bundles, said shield being composed of a material having a large product of permeability by conductivity and a ratio of permeability to conductivity substantially
different from that of the material of the conductors, said shield being in the form of a thin wide tape wound helically about the inner bundle, and the width of said tape being more than twice the pitch of the helix.

10 6. A cable comprising a plurality of conductors divided into two substantially equal groups with certain conductors of one group arranged to transmit in one direction and certain conductors of the other group arranged
15 to transmit in the opposite direction, the two groups being arranged in the form of two concentric cylindrical bundles one within the other, and a concentric shield interposed between the bundles, said shield being composed of a material having a large product
20 of permeability by conductivity and a ratio of permeability to conductivity substantially different from that of the material of the conductors, said shield being in the form of
25 a thin wide tape wound helically about the inner bundle, and the width of the tape being such with respect to its thickness and the pitch of the helix that the shield will comprise a plurality of layers of tape at each
30 point along the length of the cable and the effective laminations will approach parallelism with the surface of the shield.

35 In testimony whereof, I have signed my name to this specification this 16th day of July, 1929.

HARRY NYQUIST.

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