

March 17, 1936.

E. I. GREEN

2,034,036

CIRCUITS WITH HEXAGONAL SHIELDS

Filed June 7, 1933

5 Sheets-Sheet 1

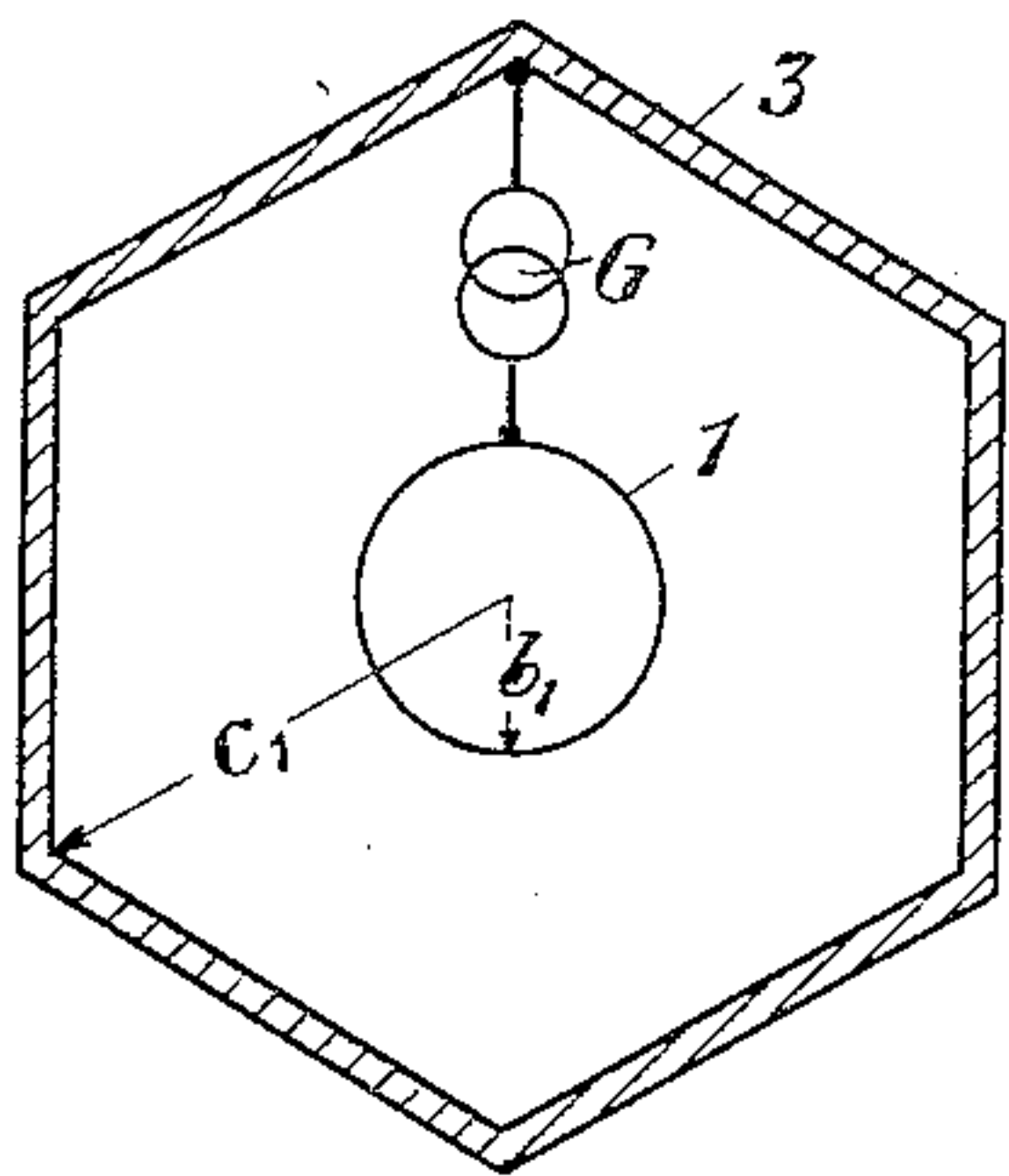


Fig. 1

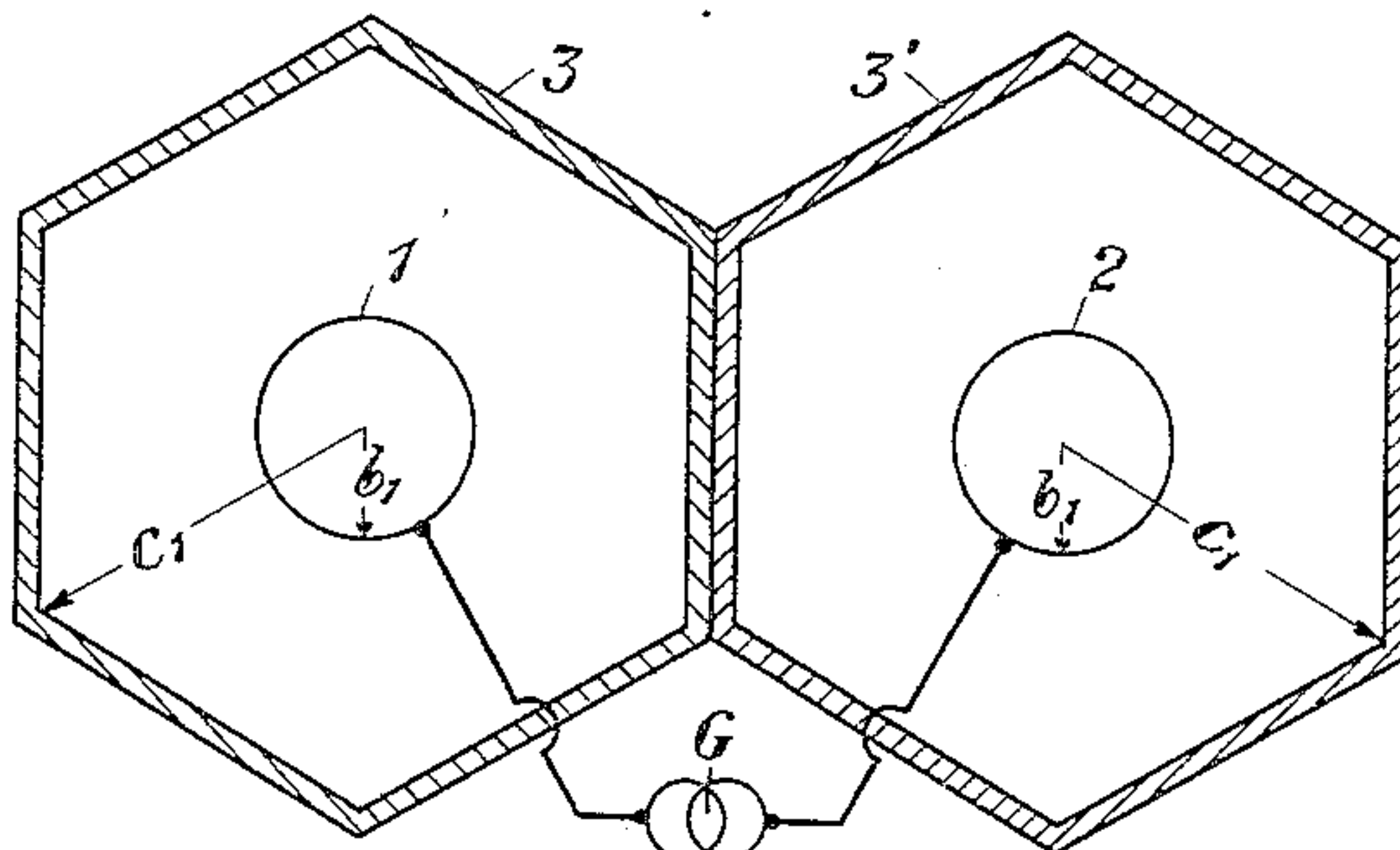


Fig. 2

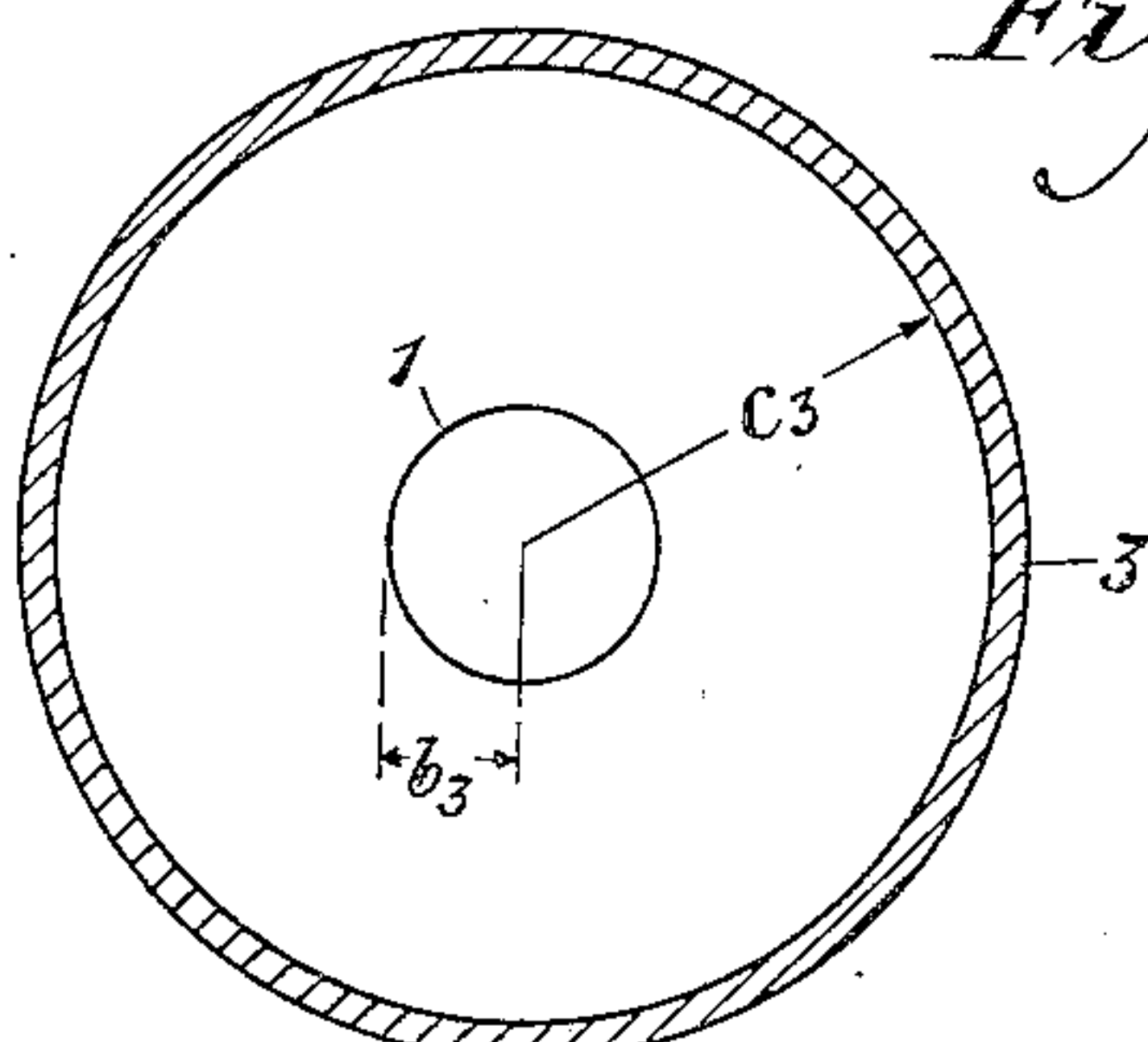


Fig. 3

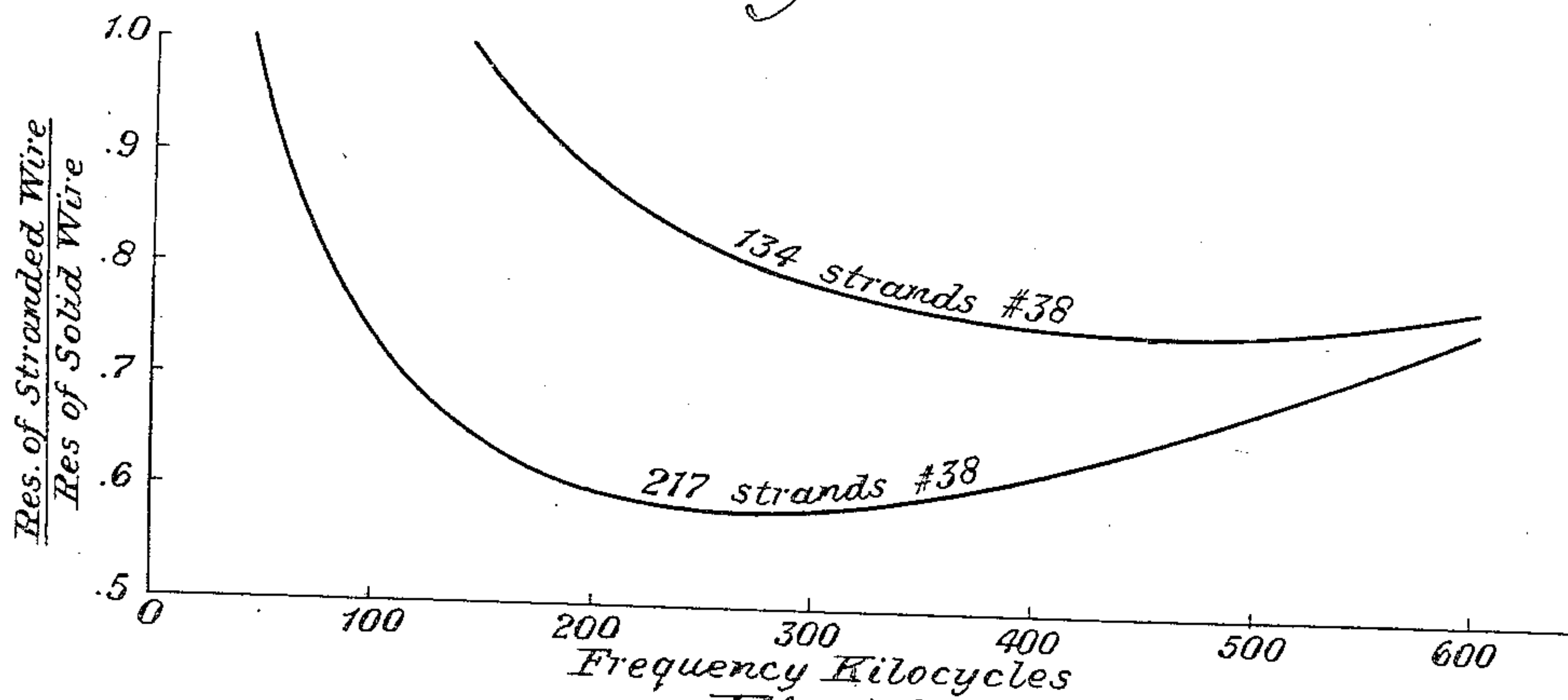


Fig. 4

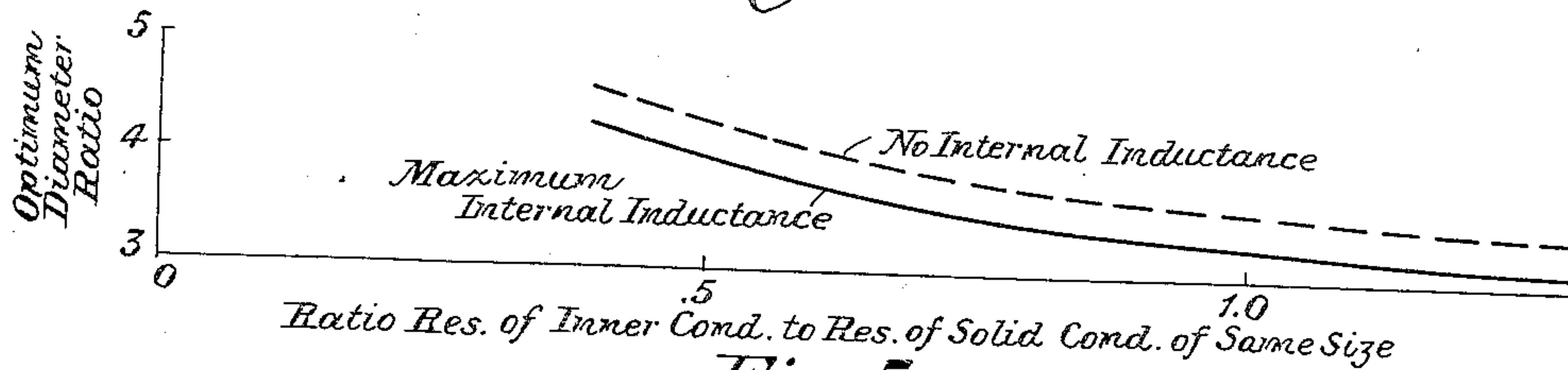


Fig. 5

INVENTOR

E. I. Green

BY

g. w. j. c.

ATTORNEY

March 17, 1936.

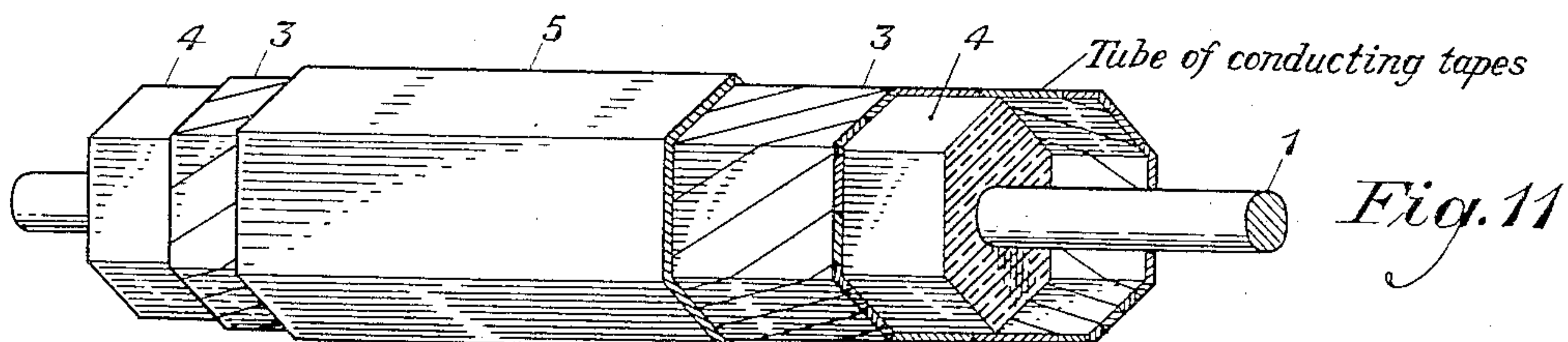
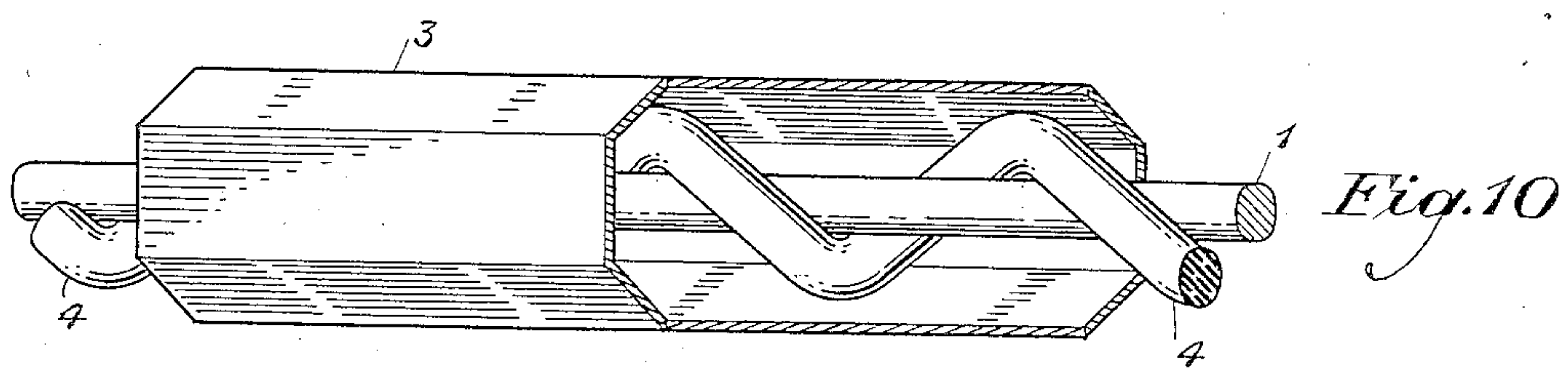
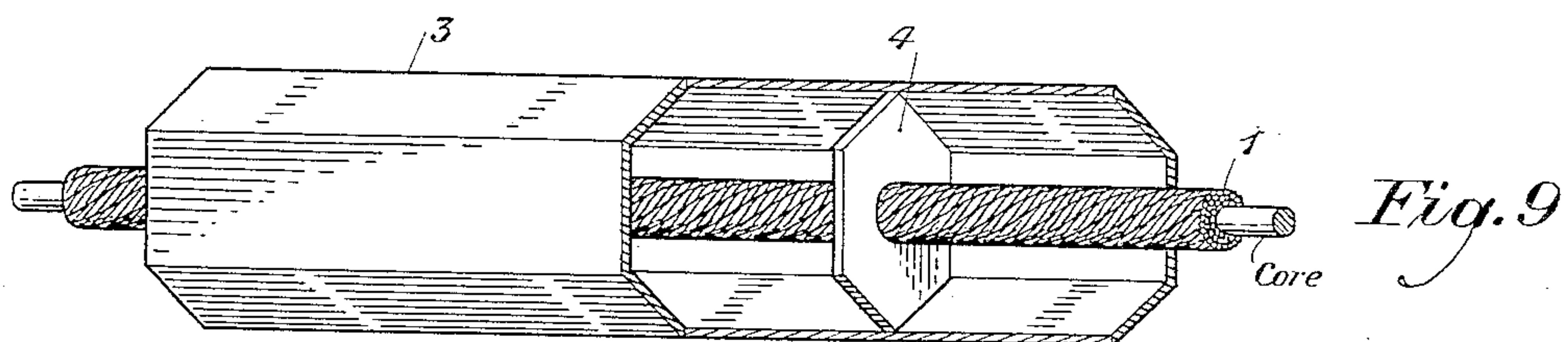
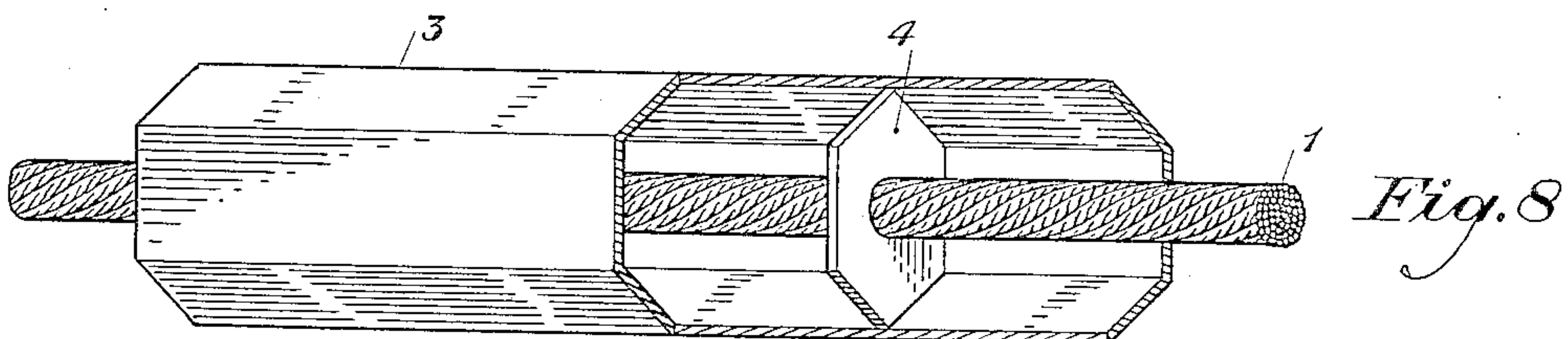
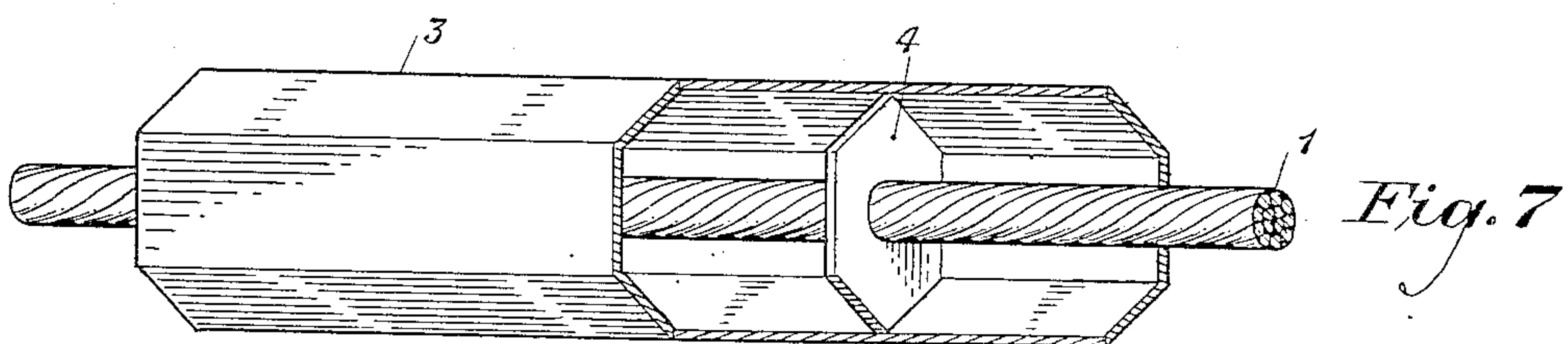
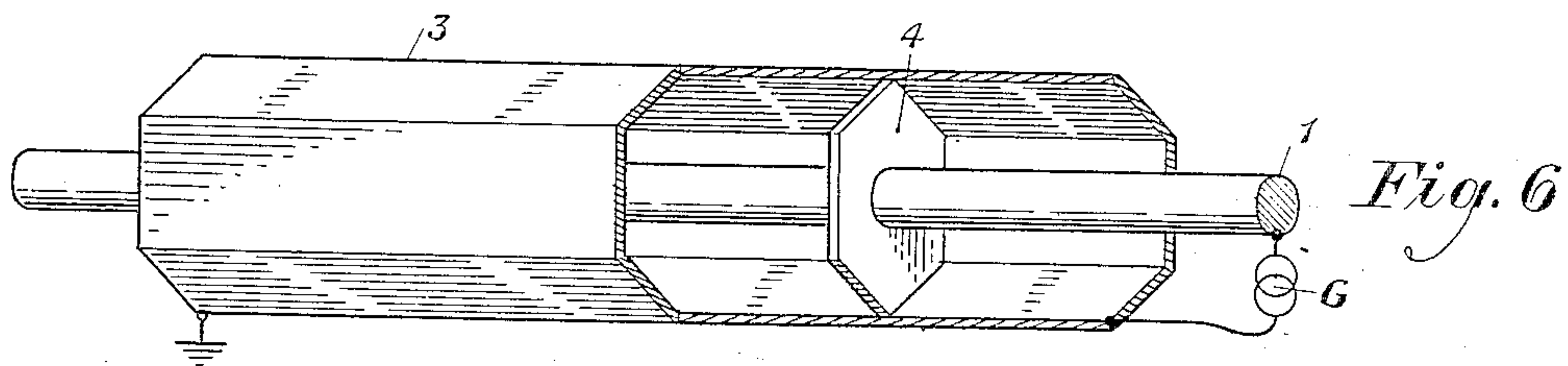
E. I. GREEN

2,034,036

CIRCUITS WITH HEXAGONAL SHIELDS

Filed June 7, 1933

5 Sheets-Sheet 2



INVENTOR
E. I. Green
BY *g. f. h. c.*
ATTORNEY

March 17, 1936.

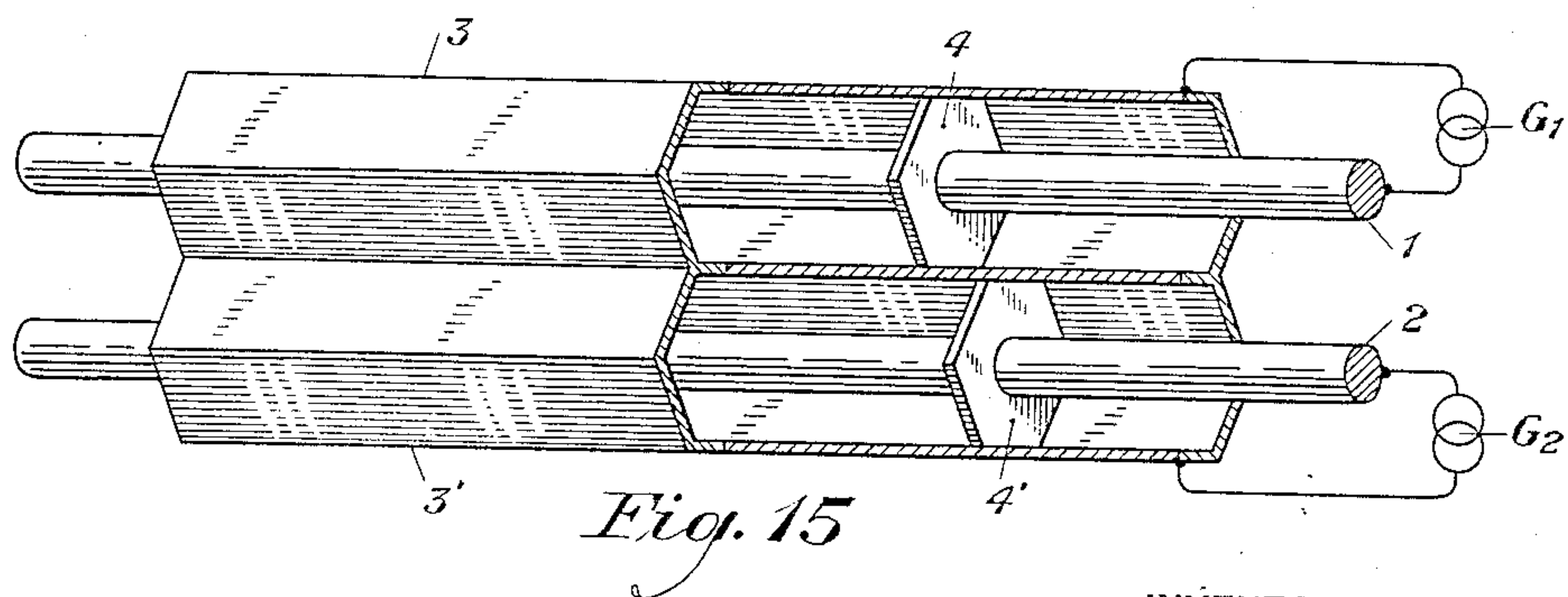
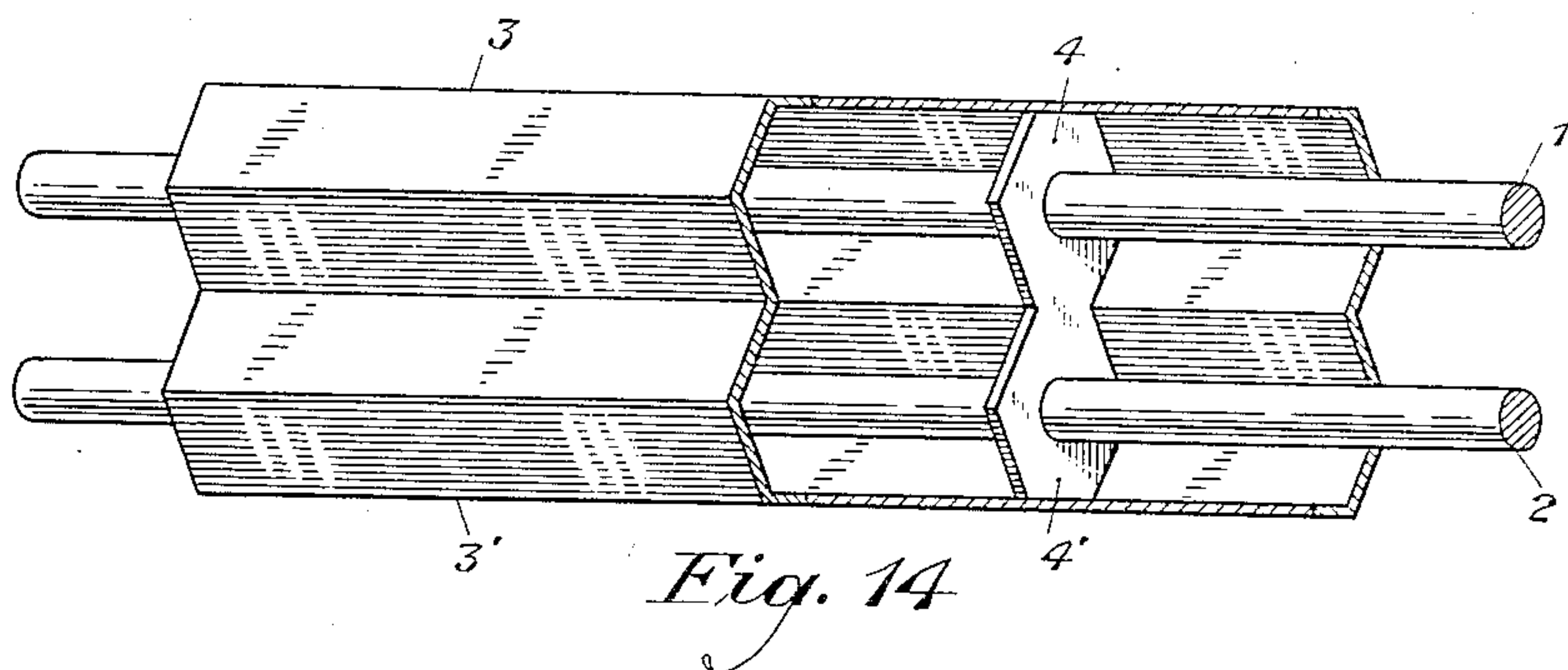
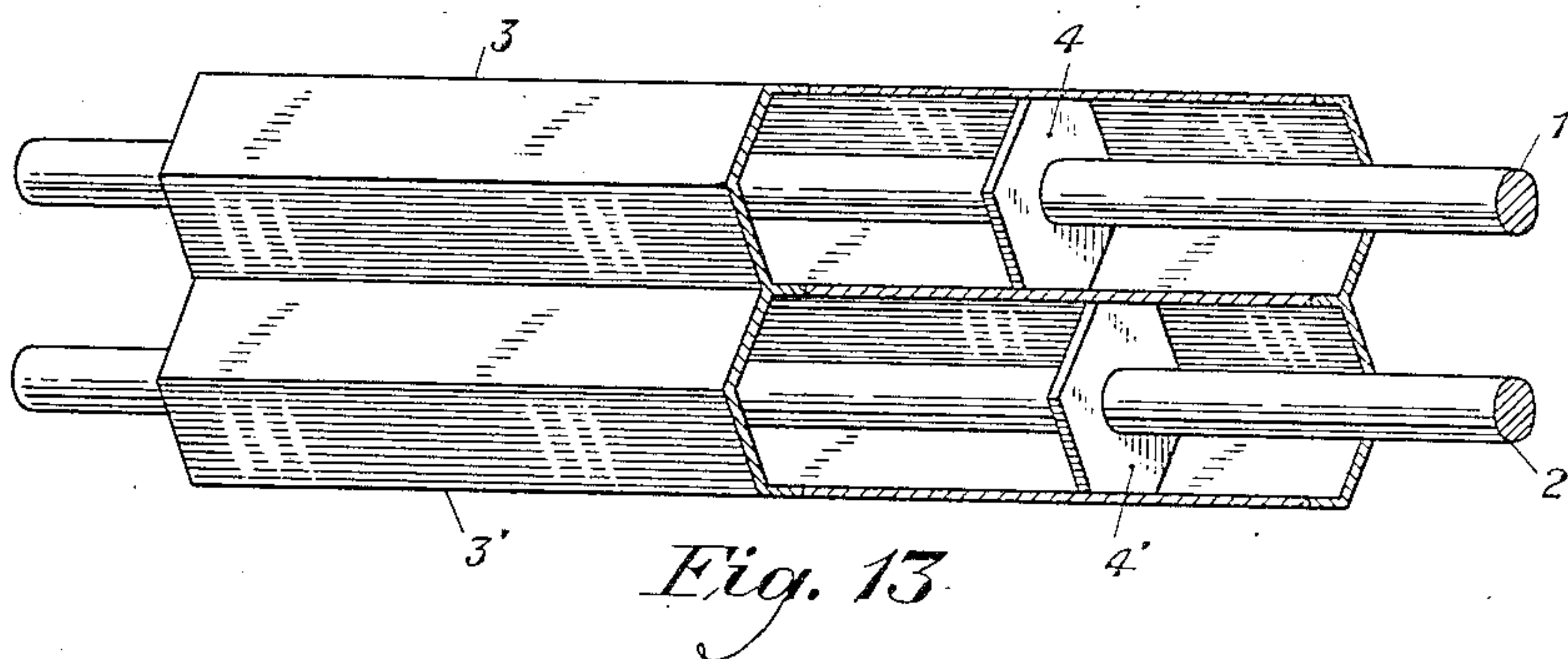
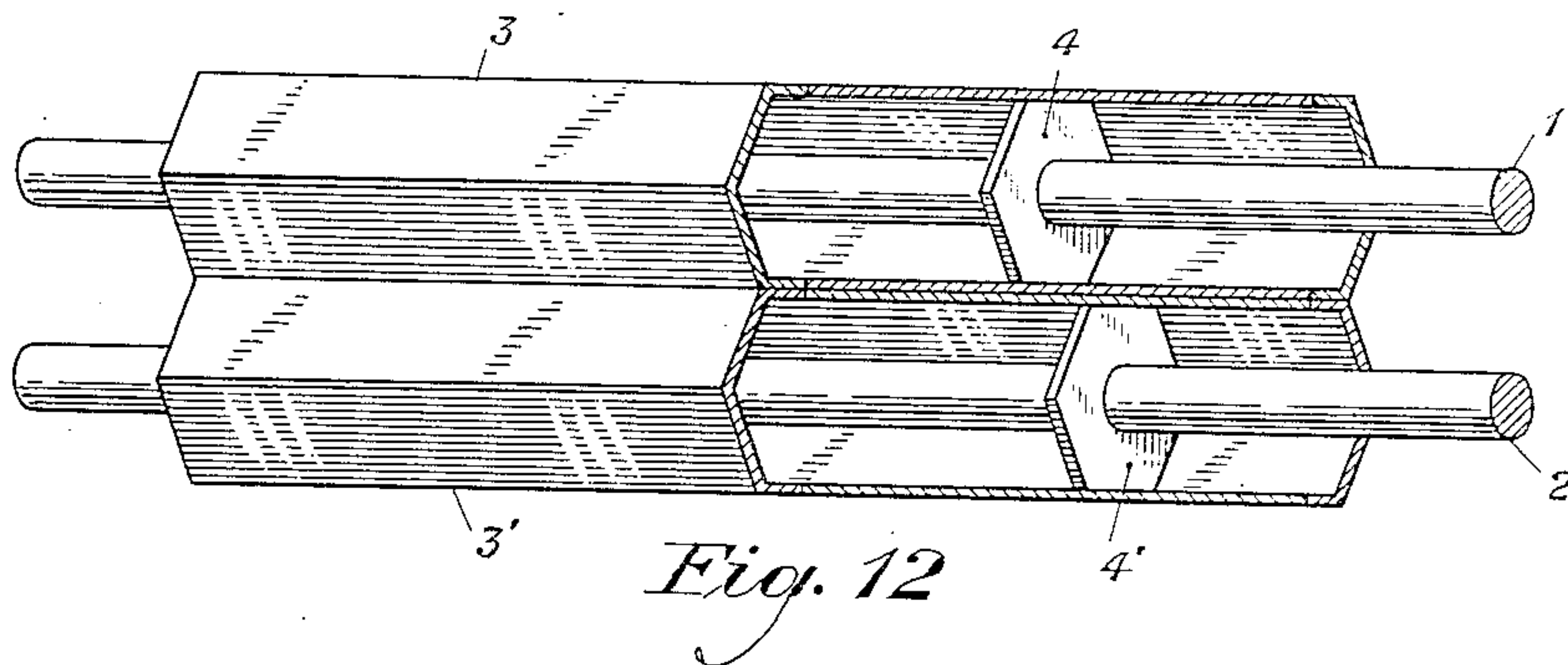
E. I. GREEN

2,034,036

CIRCUITS WITH HEXAGONAL SHIELDS

Filed June 7, 1933

5 Sheets-Sheet 3



INVENTOR
E. I. Green
BY *g. H. Fox*
ATTORNEY

March 17, 1936.

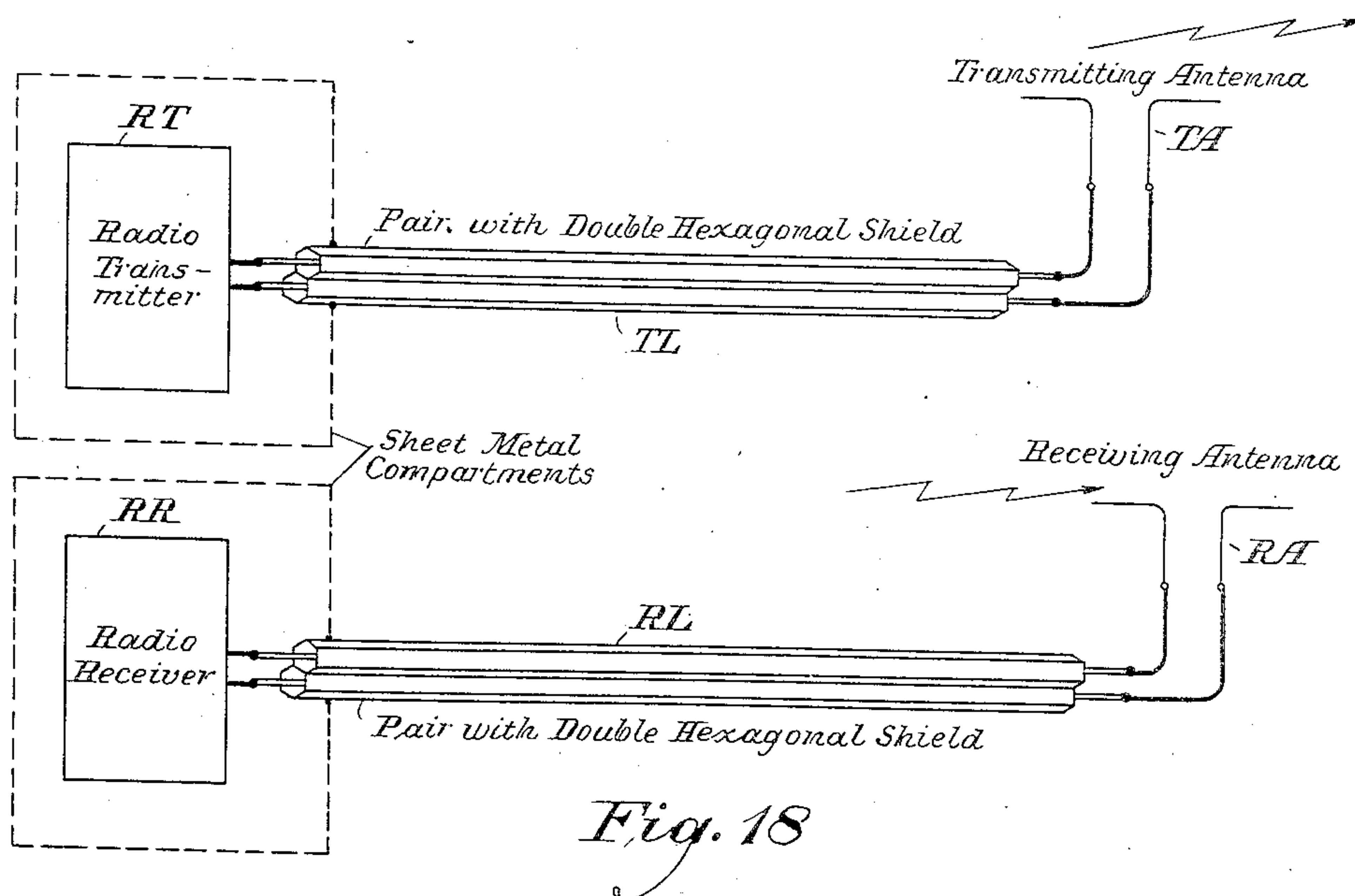
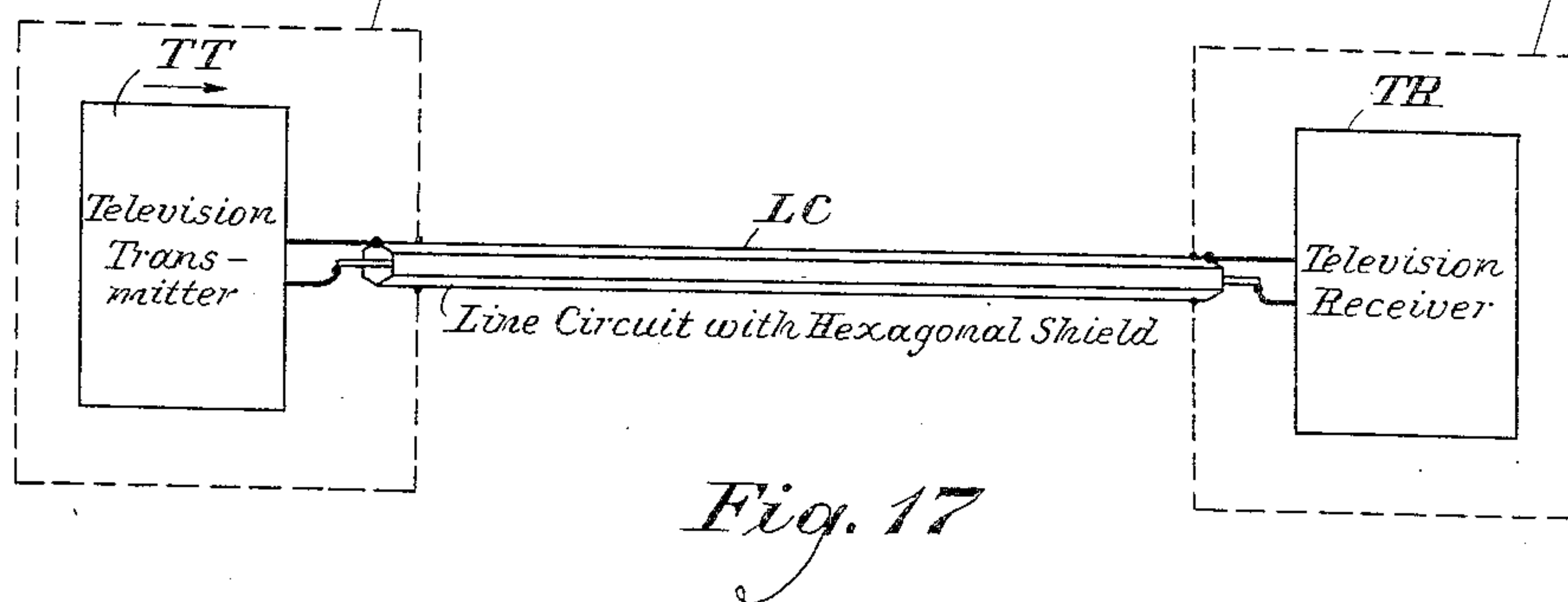
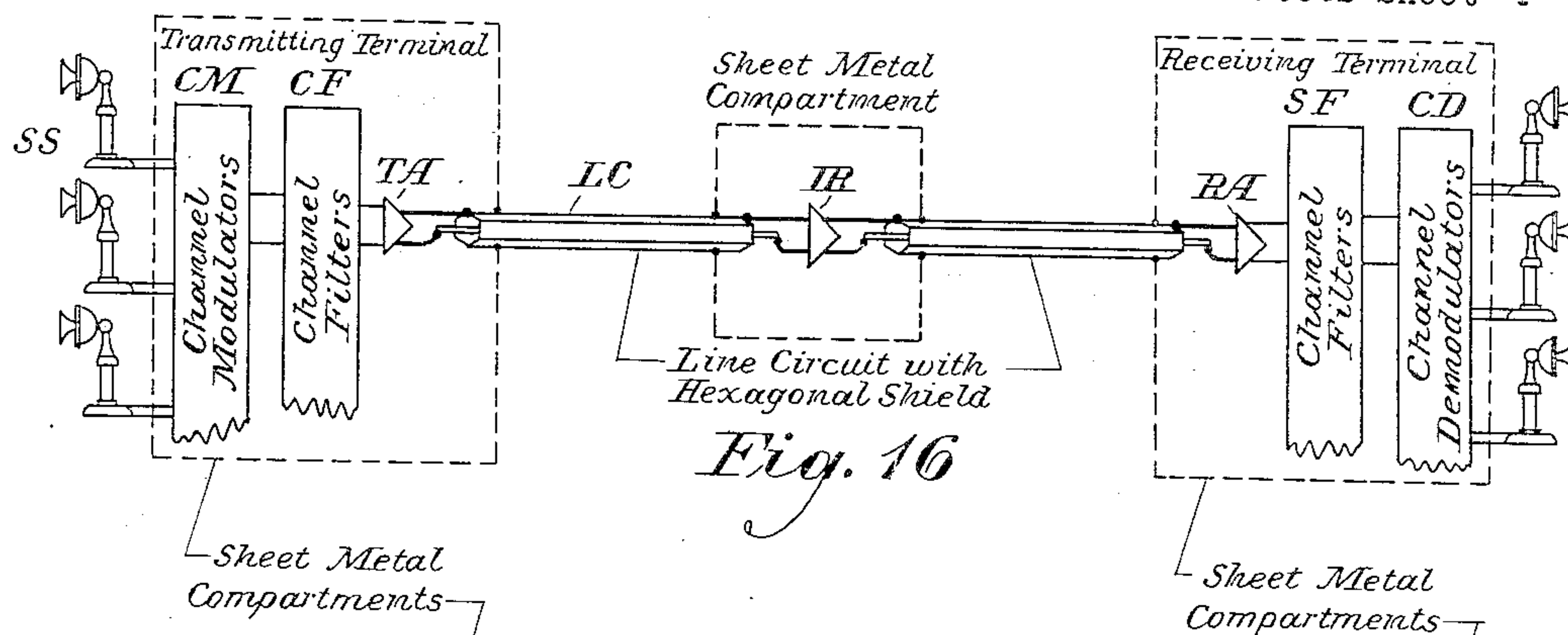
E. I. GREEN

2,034,036

CIRCUITS WITH HEXAGONAL SHIELDS

Filed June 7, 1933

5 Sheets-Sheet 4



INVENTOR
E. I. Green
BY *George*
ATTORNEY

March 17, 1936.

E. I. GREEN

2,034,036

CIRCUITS WITH HEXAGONAL SHIELDS

Filed June 7, 1933

5 Sheets-Sheet 5

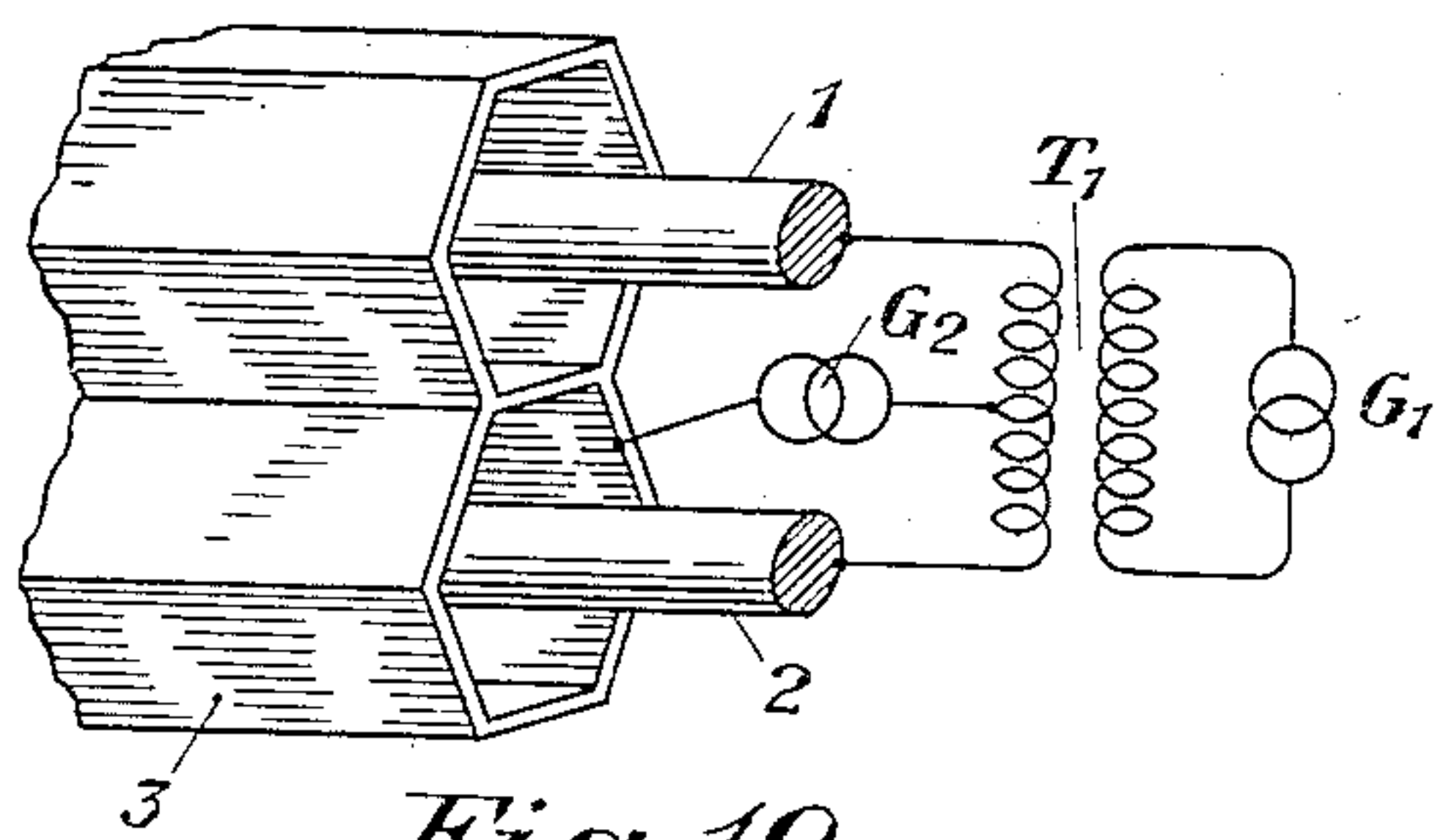


Fig. 19

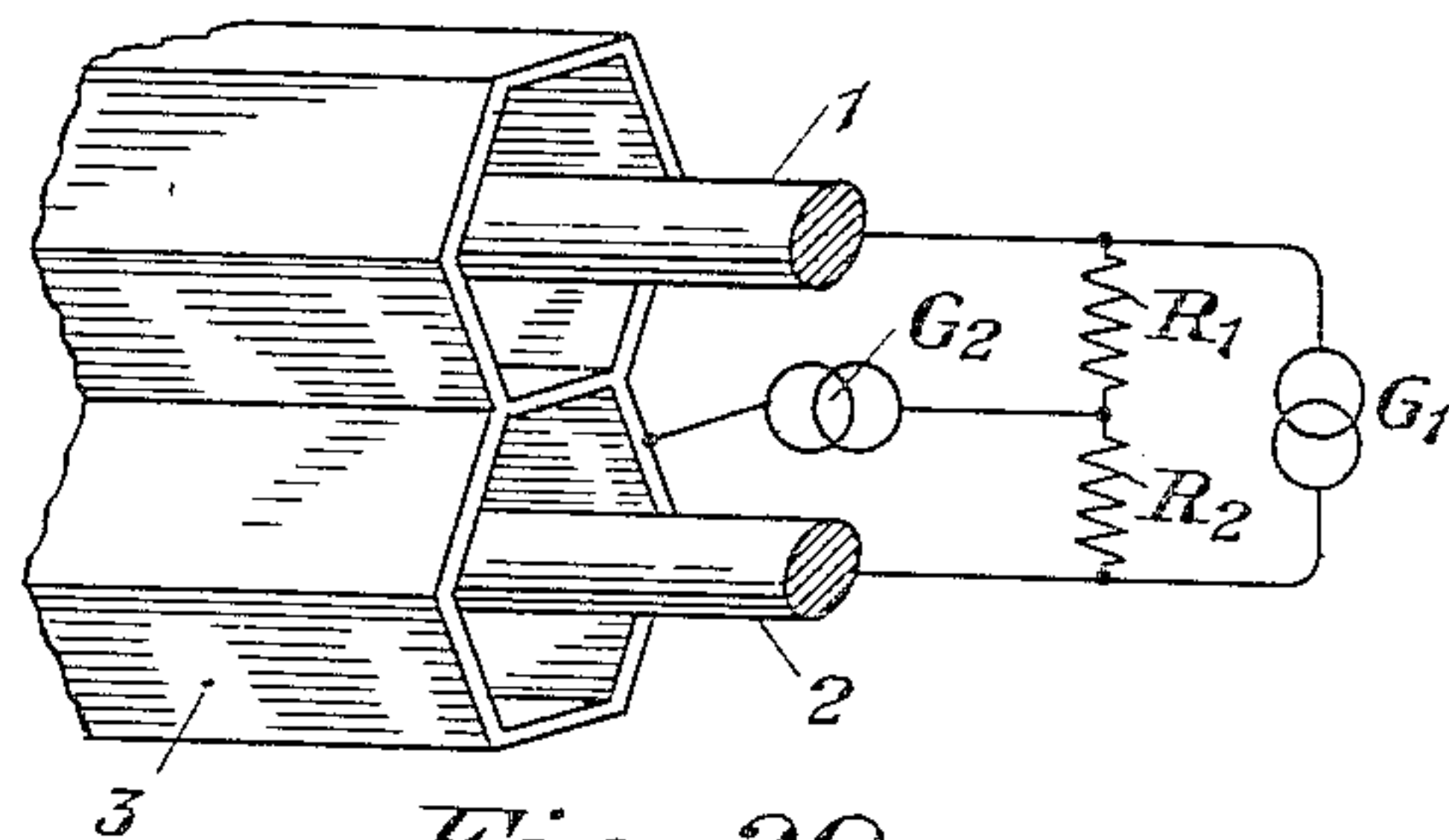


Fig. 20

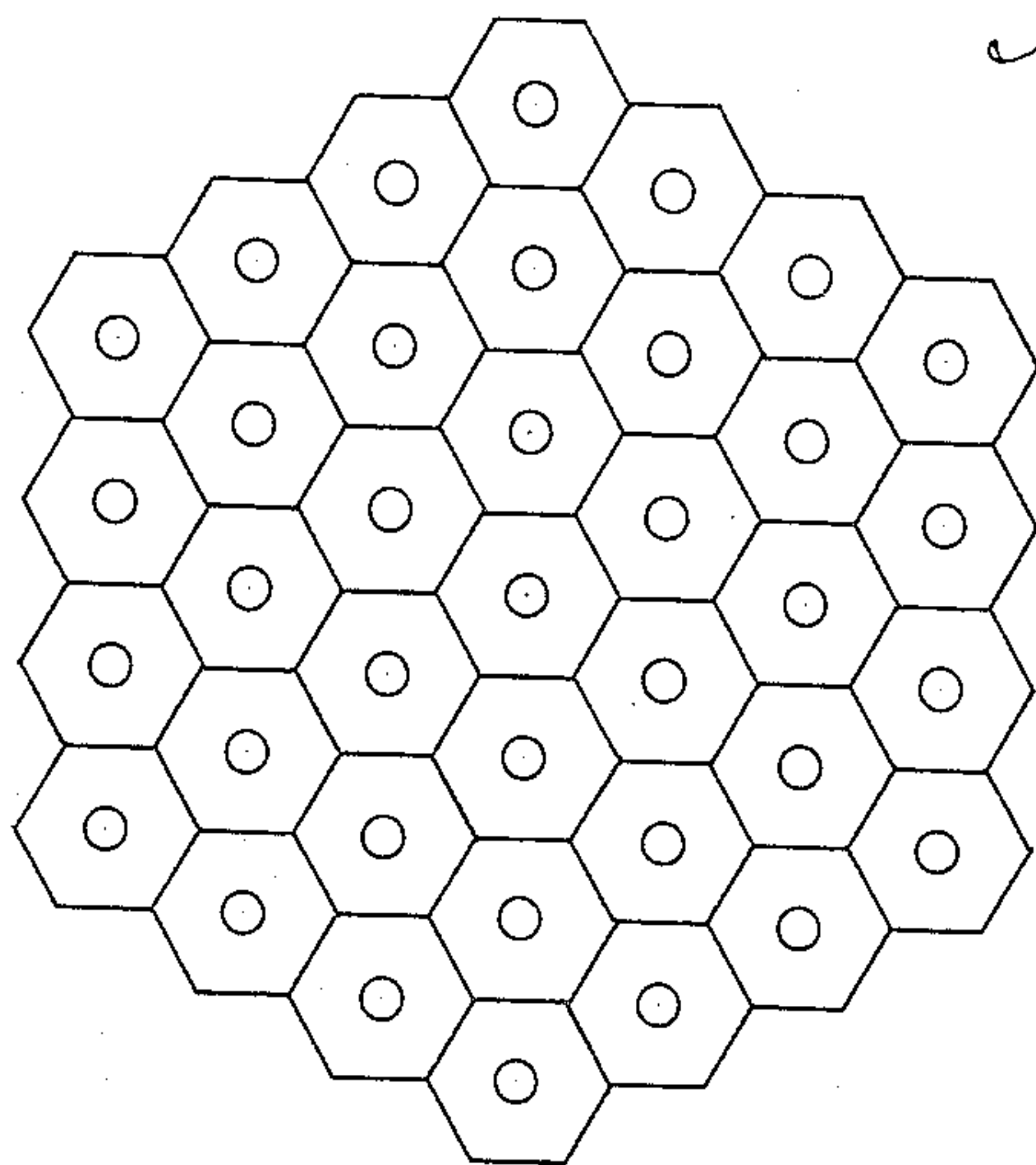


Fig. 21

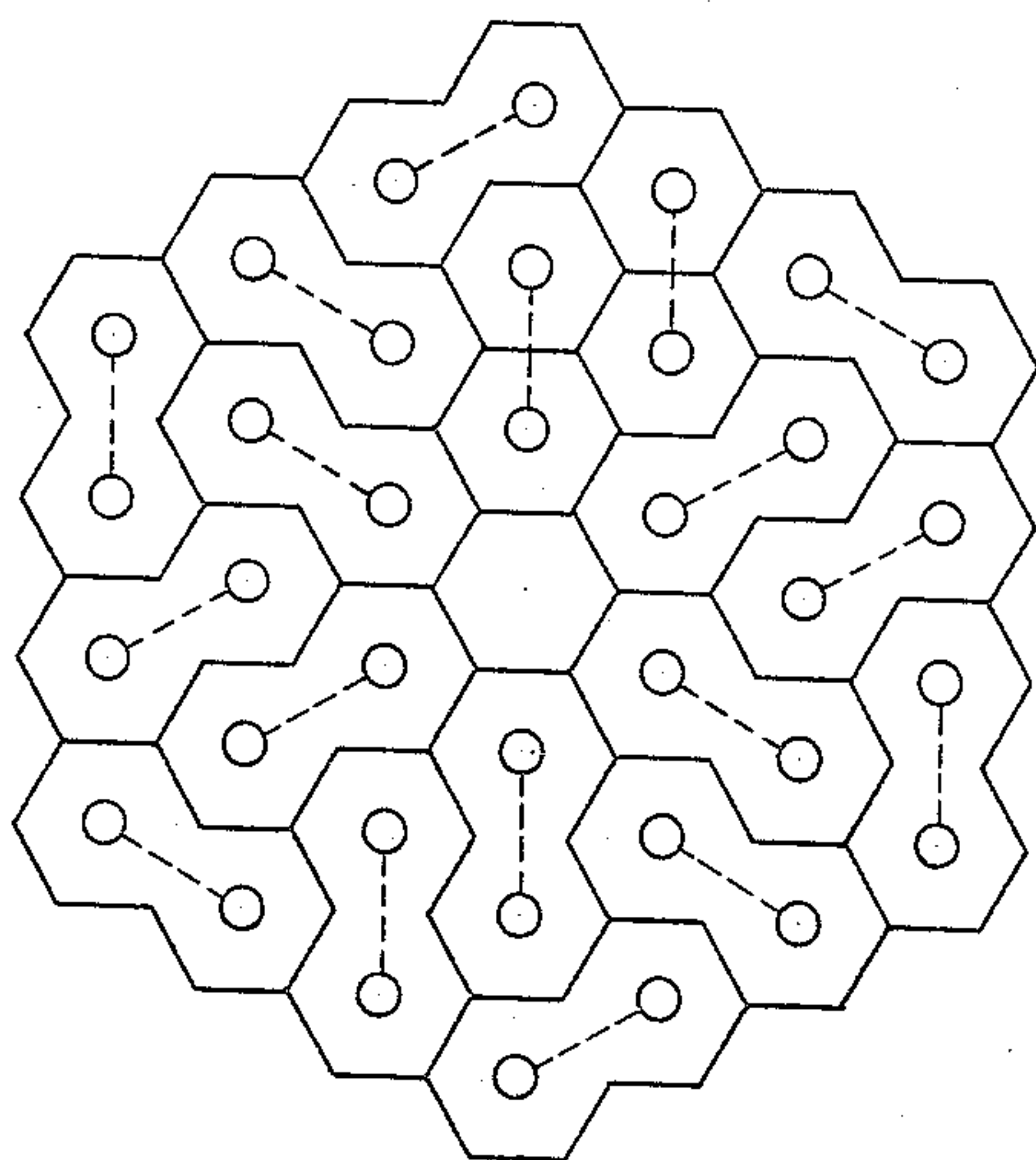


Fig. 22

INVENTOR
E. I. Green
BY *J. H. [Signature]*
ATTORNEY

UNITED STATES PATENT OFFICE

2,034,036

CIRCUITS WITH HEXAGONAL SHIELDS

Estill I. Green, East Orange, N. J., assignor to
American Telephone and Telegraph Company,
a corporation of New York

Application June 7, 1933, Serial No. 674,766

22 Claims. (Cl. 178—44)

This invention is concerned with electrical transmission circuits and has as one of its objects the securing of a transmission circuit which has the properties of low attenuation and substantial freedom from interference over a wide band of frequencies.

In determining the type of transmission circuit to be used for transmitting high frequencies or wide bands of frequencies, there are two important characteristics to be considered: (1) the susceptibility of the circuit to external disturbances such as crosstalk from nearby circuits and interference or noise from other outside sources, and (2) the high-frequency attenuation, which should be kept as low as is consistent with securing a desirable size and favorable mechanical properties. In some applications a further characteristic may be of importance, namely, that the circuit should be balanced with respect to ground.

In accordance with the present invention it is proposed to enclose the transmission circuit in a conducting shield which acts to prevent external electromagnetic or electrostatic high-frequency disturbances from causing disturbances within the circuit and conversely to prevent the currents transmitted over the circuit from causing disturbances in external circuits.

In order to reduce the high-frequency attenuation of the shielded circuit, it is proposed to secure low shunt losses by employing a dielectric having a small power factor and to reduce the series losses in the conductors by employing an insulating medium having a low dielectric constant. Accordingly, it is proposed in one embodiment of the invention to utilize a substantially gaseous dielectric. The invention comprehends also, however, the use of non-gaseous dielectric material.

The invention is particularly concerned with shielded transmission circuits derived from structures having the form of a hexagon or a double hexagon. One of the objects of the invention is the provision of a configuration for such hexagonal or double hexagonal structures which will minimize the high-frequency attenuation of the circuit.

More broadly, the invention is concerned with systems in which shielded circuits derived from hexagonal or double hexagonal structures are utilized for the transmission of high frequencies or wide bands of frequencies.

The satisfactory transmission of television images with good definition requires the transmission of a frequency band which may extend from zero frequency to hundreds or perhaps thou-

sands 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 frequency bands may be necessary for reproducing with adequate detail such scenes as a theatrical performance or an athletic event. A television band of such width might be transmitted directly over a shielded circuit designed in accordance with the principles of the invention or it might be shifted to a higher frequency position in order to avoid the necessity of transmitting the extremely low television frequencies over the line.

Moreover, by the application of multiplexing the wide frequency bands obtained from a shielded circuit designed in accordance with the invention may be used to provide substantial numbers of narrower frequency bands suitable for other communication purposes, as, for example, for telephone circuits which may require bands of about 2,500 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 services.

Also, shielded circuits of the type described herein may be advantageously employed in connecting radio antennas to radio transmitting or receiving apparatus, the circuit being 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 now be more readily understood from the following description when read in connection with the accompanying drawings in which Figure 1 is a cross-sectional diagram of a transmission circuit having the form of a hexagon; Fig. 2 is a diagram of a circuit having the form of a double hexagon; Fig. 3 is a diagram of a pair of cylindrical coaxial conductors; Fig. 4 is a curve showing the improvement in high-frequency resistance obtained with two specific designs of stranded conductors; Fig. 5 shows curves for determining the proportioning of a circuit composed of two coaxial cylindrical conductors of which the inner conductor is stranded; Fig. 6 represents a view of a hexagonal transmission structure embodying some of the principles of the invention; Figs. 7 to 15 show various other hexagonal and double hexagonal structures; Figs. 16 to 18 typify arrangements of apparatus which may be used in association with a shielded circuit designed in accordance with the invention; Figs. 19 and 20 illustrate two different

methods of deriving two independent transmission circuits from a double hexagonal structure; and Figs. 21 and 22 illustrate methods whereby structures designed in accordance with the invention may be laid up in cable form.

The coaxial type of circuit formed from two cylindrical conductors, as shown diagrammatically in Fig. 3, is well known in the art. In this figure, 1 and 3 are the inner and outer conductors, respectively, while b_3 and c_3 designate, respectively, the outer radius of the inner conductor and the inner radius of the outer conductor. The advantages of such a circuit for the transmission of high frequencies and wide bands of frequencies have been set forth elsewhere. Owing to the circular cross-section of this type of circuit, however, it is evident that when a number of such circuits are formed up into a cable, there is a certain wastage of space, with corresponding sacrifice in economy. In accordance with the present invention, it is proposed that the available space be more efficiently utilized by employing transmission structures whose exterior has the shape of a hexagon or a double hexagon.

An arrangement consisting of an inner cylindrical conductor 1 disposed coaxially with respect to a hexagonal outer conductor and shield 3 is shown diagrammatically in Fig. 1. The conductors 1 and 3 in this case are designed to be employed one as a return for the other, as indicated conventionally by the generator G. The outer conductor may be grounded if desired. The radius of the inner conductor is designated b_1 and the distance from the axis to the inner apexes of the hexagon is designated c_1 . The distance from the axis to the sides of the hexagon is then evidently

$$\frac{\sqrt{3}}{2} c_1.$$

Fig. 2 shows an arrangement which may be thought of as consisting of two of the structures of Fig. 1 placed side by side, the inner conductors being used for the transmission circuit and the outer conductors as a shield. Thus there is obtained a circuit which is balanced with respect to ground. In the figure, 1 and 2 designate the conductors and 3 and 3', which are assumed to be in contact, the two parts of the shield; b_1 designates the radius of each conductor and c_1 the distance from the axis of either conductor to an apex of the surrounding portion of the shield. The conductors 1 and 2 may be used one as a return for the other, as indicated conventionally by the generator G. The shield may be grounded if desired.

Considering the circuits of Fig. 1 and Fig. 3 from the standpoint of their being formed up with other similar circuits in a cable, it is evident that the same overall space is required with the two figures if

$$c_3 = \frac{\sqrt{3}}{2} c_1.$$

Therefore, it is interesting to compare Fig. 1 and Fig. 3 on the assumption that this relation obtains.

Considering first the capacity of the two circuits, it is apparent that when

$$c_3 = \frac{\sqrt{3}}{2} c_1$$

the circuit of Fig. 1 has the lower capacity. Moreover, it is possible to determine approximately the difference in capacity in the two cases.

As will be seen later, the value of the ratio

$$\frac{c_1}{b_1}$$

will, in general, lie somewhere between 3.8 and 5, so that the capacities of Fig. 1 and Fig. 3 may be compared in this range of values.

The capacity of the inner conductor of Fig. 1 to a concentric cylinder of radius c_1 would be

$$C_1 = \frac{\epsilon}{2 \log_e \frac{c_1}{b_1}} \text{ abfarads per cm.} \quad (1)$$

where ϵ is the dielectric constant. The capacity to a cylinder of radius

$$\frac{\sqrt{3}}{2} c_1$$

would be

$$C_2 = \frac{\epsilon}{2 \log_e \left(.866 \frac{c_1}{b_1} \right)} \text{ abfarads per cm.} \quad (2)$$

Equation (2), of course, represents the capacity of Fig. 3 for the same space requirement in a cable as Fig. 1.

The capacity of the hexagonal arrangement lies somewhere between these two values and to a first approximation it might be represented by the average of the two which is

$$C_3 = \frac{\epsilon \log_e \left(.931 \frac{c_1}{b_1} \right)}{2 \log_e \frac{c_1}{b_1} \times \log_e \left(.866 \frac{c_1}{b_1} \right)} \text{ abfarads per cm.} \quad (3)$$

However, if we consider the diagram, it will be obvious that the area of the inscribed circle of Equation (2) is closer to the area of the hexagon than is the area of the circumscribed circle of Equation (1). Furthermore, the departures of the hexagon outwardly from the inscribed circle will produce less change in capacity than the departures inwardly from the circumscribed circle. Hence, it is obvious that the capacity of the hexagon is closer to C_2 than to C_1 , and it must consequently lie between C_3 and C_2 .

Further consideration, however, shows that the capacity of the hexagon must be closer to C_3 than it is to C_2 since C_3 represents the capacity to a circle which has about equal areas of the hexagon within and without its circumference. Hence, the capacity of the hexagon lies somewhere between C_3 and the average of C_3 and C_2 which is

$$C_4 = \frac{\epsilon \log_e \left(.965 \frac{c_1}{b_1} \right)}{2 \log_e \frac{c_1}{b_1} \times \log_e \left(.866 \frac{c_1}{b_1} \right)} \text{ abfarads per cm.} \quad (4)$$

As a final approximation, therefore, the capacity of the hexagon may be taken as approximately equal to the average of C_3 and C_4 , namely

$$C_5 = \frac{\epsilon \log_e \left(.949 \frac{c_1}{b_1} \right)}{2 \log_e \frac{c_1}{b_1} \times \log_e \left(.866 \frac{c_1}{b_1} \right)} \text{ abfarads per cm.} \quad (5)$$

For the usual range of values of the ratio

$$\frac{c_1}{b_1}$$

C_5 probably represents the capacity of the hexagon to an accuracy of better than 1 per cent.

If the value of

$$\frac{c_1}{b_1}$$

is assumed to be 4, the capacity for Fig. 1 as given

by Equation (5) is found to be 4 per cent. less than the capacity of Fig. 3 as given by Equation (2).

Since the high-frequency inductance varies inversely with the capacity, the inductance of Fig. 1 will be correspondingly larger than that of Fig. 3

$$\left(\text{assuming } c_3 = \frac{\sqrt{3}}{2} c_1 \right)$$

Hence the high-frequency characteristic impedance for Fig. 1 will be greater than for Fig. 3. the ratio of the impedance being the inverse of the ratio of capacities. This difference in high-frequency impedance is significant, since for a circuit with zero leakage, other things being equal, the high-frequency attenuation varies inversely with the impedance.

By a similar process of reasoning it may be shown that the double hexagonal circuit of Fig. 2 has a higher characteristic impedance than a similar circuit derived from two sets of concentric cylinders.

For some applications the arrangements of Fig. 1 or Fig. 2 might be employed without any consideration of the particular proportioning which results in minimum high-frequency attenuation for a given cross-sectional area. It has been found, however, that for many purposes the cost of a transmission circuit may be considered as roughly proportional to the space occupied by the circuit. This applies especially if the circuit in question is one of a number of circuits which are formed up into a cable. Accordingly, it is desirable to determine the configuration for the circuits of Figs. 1 and 2 which will give minimum high-frequency attenuation for a given cross-sectional area.

This problem may be considered in two parts: first, the case in which the conductor or conductors inside the shield are solid or are otherwise constructed in such a manner that the high-frequency currents travel along the conductor surface, and second, the case in which the conductor or conductors are composed of insulated strands which are interwoven so as to distribute the high-frequency currents throughout the conductor cross-section. The first of these cases will now be taken up.

Referring to the circuit of Fig. 3 it can be shown that there is a particular value for the ratio

$$\frac{c_3}{b_3}$$

which makes the high frequency attenuation of the circuit a minimum. This optimum value may be determined as follows:

The high-frequency resistance, inductance and capacity of the circuit, which may be designated R_3 , L_3 and C_3 , respectively, may be approximately represented by the following well-known formulas:

$$R_3 = K_0 \sqrt{f} \left(\frac{1}{b_3} + \frac{1}{c_3} \right) \quad (6)$$

$$L_3 = K_1 \log_e \frac{c_3}{b_3} \quad (7)$$

$$C_3 = \frac{K_2 \epsilon}{\log_e \frac{c_3}{b_3}} \quad (8)$$

where K_0 , K_1 and K_2 are constants, f is the frequency and ϵ is the dielectric constant of the insulating medium.

The high-frequency attenuation of the circuit

may be closely approximated by the following formula:

$$\alpha = \frac{R_3}{2} \sqrt{\frac{C_3}{L_3}} + \frac{G_3}{2} \sqrt{\frac{L_3}{C_3}} \quad (9)$$

where G_3 is the leakage conductance of the circuit. Let it be assumed that the dielectric is largely gaseous, so that the leakage conductance may be assumed to be zero. If the cross-sectional area occupied by the circuit is to be constant, the value of c_3 may be assumed constant. Hence, on substituting the values for R_3 , L_3 and C_3 in (9), there results the following:

$$\alpha = K_3 \frac{\left(1 + \frac{c_3}{b_3} \right)}{\log_e \frac{c_3}{b_3}} \quad (10)$$

where

$$K_3 = \frac{K_0 \sqrt{f}}{2} \sqrt{\frac{K_2 \epsilon}{K_1}} \frac{1}{c_3}.$$

On minimizing Equation (10) with respect to

$$\frac{c_3}{b_3},$$

it is found that the condition for minimum high-frequency attenuation in the circuit of Fig. 3, when using a solid inner conductor or its equivalent, is:

$$\frac{c_3}{b_3} = 3.59 \quad (11)$$

Comparing Fig. 3 and Fig. 1, it is clear that the value of the expression

$$\frac{\sqrt{3} c_1}{2 b_1}$$

for minimum high-frequency attenuation in Fig. 1 should be slightly greater than 3.59, that is to say,

$$\frac{c_1}{b_1}$$

should be slightly greater than about 4.14. By a similar process of reasoning it may be shown that the value of the ratio

$$\frac{c_1}{b_1}$$

which makes the high-frequency attenuation for the circuit of Fig. 2 a minimum is likewise slightly greater than 4.14. For practical purposes a value of about 4.3 may be used.

The case where conductor 1 in Fig. 1 or conductors 1 and 2 in Fig. 2 are composed of insulated strands will now be considered. As will be pointed out later, such stranding may be accomplished in various ways. Ordinarily the purpose of stranding would be to counteract the tendency of the high-frequency currents to concentrate on the surface of the conductor, and thereby to reduce the high-frequency resistance of the conductor at high frequencies, and increase its internal inductance. Both of these results tend to decrease the high-frequency attenuation of the circuit. 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.

The high-frequency resistance of one stranded

conductor alone (in abohms per centimeter) may be written as

$$\frac{n}{b_1} \sqrt{\frac{f}{\lambda}}$$

where b_1 and f have the same significance as before, λ is the conductivity (approximately 5.8×10^{-4} abohms per centimeter cube for copper) and n is the ratio of the resistance of the stranded conductor to the resistance of a solid conductor of the same diameter at the same high frequency f .

The value of n for a conductor which is stranded in such a manner that the current density is uniform throughout its 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 involving D^2 , when it will read:

$$R' = R_0 \left[\left(1 + \frac{\alpha^2}{2} \right) (1 + F) + \frac{2S^2 \delta^2 G}{d_0^2} \right] \quad (12)$$

This equation gives the A. C. resistance of one stranded conductor in abohms per centimeter. The high-frequency resistance R_1' of a solid wire is given by the expression

$$\frac{1}{b_1} \sqrt{\frac{f}{\lambda}}$$

The value of n may be determined by dividing R' by R_1' .

Fig. 4 shows how the value of n varies with frequency for two assumed conditions of stranding. It will be observed that the value of n may be made considerably less than unity at frequencies in the vicinity of 500 kilocycles or above. By the use of Equation (12) the stranded conductor or conductors may be designed so as to have as low a value of n as practicable at the maximum frequency to be transmitted over the circuit.

As pointed out below, it would be possible, instead of filling up the complete conductor cross-section with insulated strands, to arrange the strands in an annular cross-section, the stranding being carried out in such a way that the path of any individual strand would extend between the outer and inner circumferences of the annulus. If the conductors are stranded in this or some other manner, the value of n may be determined by computation or experiment.

Another important effect to be obtained by stranding is an increase in the internal inductance of the conductor. With a solid wire the current at high frequencies crowds to the surface so that the internal inductance is so small as to be practically negligible. With a stranded conductor a substantial amount of internal inductance may be obtained. With a completely stranded cross-section this internal inductance becomes very nearly equal to the D. C. internal inductance of a solid wire which is .5 abhenry per centimeter. For a stranded conductor of annular cross-section the internal inductance would evidently lie somewhere between this value and zero, depending upon the dimensions of the annulus. The value of the internal inductance of a conductor of annular cross-section, assuming that the current density is uniform, is given by the following equation:

$$L_i = \frac{1}{2} - \frac{1}{\rho^2 - 1} + \frac{2 \log_e \rho}{(\rho^2 - 1)^2} \text{ abhenries per cm.} \quad (13)$$

where ρ is the ratio of the outer to the inner radius of the annulus.

Thus when the conductor 1 of Fig. 1 or the conductors 1 and 2 of Fig. 2 are stranded, the high-frequency attenuation may, by virtue of the lower resistance and the internal inductance resulting from stranding, be reduced below the value which would be secured with solid conductors. The improvement obtained in this manner may be taken advantage of in either of two ways: (1) If it is desired to obtain a given attenuation at a certain frequency, the diameter of the outer conductor and hence the amount of conductor material and the space occupied may be considerably reduced, or (2) if the diameter of the outer conductor be held fixed, the frequency at which a given attenuation is obtained may be increased.

Knowing the values of the resistance ratio n and the internal inductance L_i which may be secured by stranding, the next step is to determine the optimum proportioning for Fig. 1 or Fig. 2 with stranding. Using the basic attenuation Equation (9), the attenuation of the circuit of Fig. 3 with a stranded inner conductor, assuming zero leakage, may be written as follows:

$$\alpha = \frac{K_4(1 + nx)}{\sqrt{2(\log_e x)^2 + L_i \log_e x}} \quad (14)$$

where x equals

$$\frac{c_3}{b_3} \quad (30)$$

and K_4 is a constant. In order to determine the optimum ratio of radii

$$\frac{c_3}{b_3} \quad (35)$$

which will give minimum attenuation, Equation (14) should be minimized with respect to x . This procedure shows that the minimum attenuation is obtained when the following relation is satisfied:

$$\frac{2nx \log_e x}{nx + 1} = \frac{4 \log_e x + L_i}{2 \log_e x + L_i} \quad (15)$$

The values of x obtained from this expression are plotted in Fig. 5, where the solid curve is based on the assumption that the internal inductance of the stranded conductor is equal to the D. C. internal inductance of a solid wire (.5 abhenry per centimeter), while the dotted curve assumes that the internal inductance of each stranded conductor is zero. For a completely stranded cross-section, the lower curve (solid) is substantially correct, while for annular stranding the value of the optimum ratio of radii will lie somewhere between the two curves.

Comparison of Fig. 1 and Fig. 3 shows that for minimum high-frequency attenuation in Fig. 1 the value of the quantity

$$\frac{\sqrt{3} c_1}{2 b_1} \quad (60)$$

in Fig. 1 should be somewhat greater than the values given in Fig. 5. In other words, the optimum value of the ratio

$$\frac{c_1}{b_1} \quad (65)$$

for Fig. 1 should be slightly more than

$$\frac{2}{\sqrt{3}} \quad (70)$$

times the values shown in Fig. 5. It will be seen that for the usual values of n , the values for the ratio of radii range, in general, between about 3.8 and 5, and may depart quite materially from

the value of about 4.3 which obtains in the case of solid conductors. Hence, in order to utilize the stranding most effectively, it is desirable to design the circuit in accordance with the relations given above.

By a similar process of reasoning it may be shown that the optimum values for the ratio

$$\frac{c_1}{b_1}$$

in Fig. 2 should likewise be slightly greater than

$$\frac{2}{\sqrt{3}}$$

times the values given in Fig. 5.

The foregoing derivation of the proportioning of a circuit with hexagonal outer conductor in order to obtain minimum high-frequency attenuation has largely been directed toward the cases where the insulating medium is largely gaseous so that the dielectric constant is substantially unity and a leakage conductance substantially zero. It can be shown, however, that the optimum proportioning will remain substantially unchanged for other types of dielectric. Thus if the space between conductors and shield is filled with a homogeneous non-gaseous dielectric as, for example, rubber or oil, the ratios giving minimum high-frequency attenuation should be the same as for a gaseous dielectric. This will also be the case when a mixture of dielectrics is employed, for example, a combination of gaseous and non-gaseous dielectrics provided that the arrangement of the dielectric is such as not to distort the path which would be assumed by the dielectric flux if the dielectric medium were entirely gaseous. Where a combination of dielectrics is employed in such a manner as to produce such distortion of the flux, the ratio for optimum proportioning may be changed to some extent but, in general, characteristics approaching the optimum will be obtained for the values which have previously been set forth.

Some of the fundamental principles of the invention having now been set forth, consideration may be given to types of structures in which these principles may be incorporated. Fig. 6 represents a view of a transmission structure consisting of a solid inner conductor 1 disposed co-axially with respect to a hexagonal outer conductor and shield 3. The two conductors are held in position with respect to one another by insulating spacers 4 or other suitable devices. The conductors of the pair are connected one as a return for the other, as is indicated conventionally by the generator G. If desired, the shield may be grounded as indicated on the drawings.

The conductor 1 may be of such a type that currents of frequencies well above the audible range travel substantially on its outer surface. For example, this conductor may be a solid wire or may be tubular. If a tubular inner conductor is employed, its wall thickness will ordinarily depend upon mechanical rather than electrical considerations, since only a very thin wall is required for the conduction of the high frequency currents.

Also, the inner conductor may consist of a cylindrical assembly of conducting strips, tapes, ribbons, wires or the like, which are not insulated from one another. Such a form of construction might be particularly desirable where a flexible structure is required. One construction of this type is indicated in Fig. 7, the inner conductor 1

in this case being composed of uninsulated wires stranded together.

As has already been pointed out, it may be advantageous to construct the conductor 1 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. With a suitable method of stranding, the high-frequency current may be distributed substantially uniformly over the conductor cross-section. One method of securing 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, 3) 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 method any one strand, in going along the conductor, travels a path back and forth between the center of the conductor and its periphery. A structure employing an inner conductor stranded in this manner is illustrated in Fig. 8.

Instead of being twisted together as described above, the strands might be interwoven or braided in other ways so as to produce the desired effect. Also, it would be possible, as already noted, 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 strength or rigidity. The stranding might preferably be designed in such a way that the path of any strand would extend between the inner and outer circumferences of the annulus. A structure employing a stranded conductor of annular cross-section is illustrated in Fig. 9.

Any of various forms or shapes might be employed for the insulation between the conductors 1 and 3. One possible arrangement would be to use a continuous spirally applied string or strip of dielectric material around the conductor. An arrangement of this type is illustrated in Fig. 10 where 4 is a string or strip of dielectric material separating the conductors 1 and 3. Generally, it will be desirable that the amount of insulating material be a minimum in order that the dielectric may be largely gaseous. In some cases, however, it will be found advantageous to use a dielectric which is partly or wholly non-gaseous, as, for example, rubber insulation. A structure with a dielectric 4 of this kind is shown in Fig. 11. For the insulation arrangements that would ordinarily be employed in practice, the optimum configuration of the circuit will be approximately the same as for the assumed condition of a gaseous dielectric.

The outer conductor and shield 3, instead of consisting of a solid hexagonal tube, might consist of a hexagonal assembly of conducting strips, tapes, wires, ribbons or the like. Such a form of construction might be particularly advantageous where a flexible structure is required. If desired, the outer conductor may be surrounded by a waterproof sheath or covering 5 which may be composed of lead, rubber or other suitable material as illustrated in Fig. 11.

In connection with the shield, it may be noted that in addition to performing an electrical function by protecting against inductive effects, it may

be useful in affording mechanical protection to the circuit and thereby permitting the use to a considerable extent of an air dielectric. Due to skin effect, the high-frequency currents will penetrate only a little way into the outer conductor so that the electrical requirements are satisfied by a comparatively thin wall. Consequently, the thickness of the outer conductor will ordinarily be determined by mechanical considerations.

The shielding effect of the outer conductor will usually make it possible, where desired, to allow the signals transmitted over the circuit to drop down to a minimum level, determined by the noise due to thermal agitation of electricity in the conductors. Hence, the shielding effect facilitates the spacing of intermediate amplifiers in the circuit at wider intervals than would otherwise be possible.

In order to obtain a balanced transmission circuit of double hexagonal cross-section, pairs of structures of any of the types illustrated in Figs. 6 to 11 might be placed side by side, the inner conductors being used one as a return for the other to form the transmission circuit and the outer conductors forming the shield. One such arrangement, comprising a pair of structures of the type illustrated in Fig. 6, is shown in Fig. 12, where 1 and 2 are the conductors, shown as solid wires, and 3 and 3', which are assumed to be in contact, serve as the shield.

The shield employed with the double hexagonal circuit, instead of consisting of two parts as shown in Fig. 12, might be a single "double-barreled" arrangement as shown in Fig. 13. In this case, one wall is common to the two halves of the structure. Moreover, a structure suitable for a balanced circuit would still be obtained if this common wall were omitted as shown in Fig. 14.

It should be noted also that the double-barreled type of shield, as shown in Fig. 13, might be used in obtaining two unbalanced circuits, the shield being combined with any of the arrangements of inner conductor and insulation shown in Figs. 6 to 11. One such arrangement of this kind for obtaining two unbalanced circuits is shown in Fig. 15.

The structures which have been illustrated in Fig. 6 to Fig. 15, comprising hexagonal or double-hexagonal arrangements of conductors and shields, may be employed as transmission media for various types of transmission systems. Some of the systems which may be used in this manner are illustrated schematically in Figs. 16 to 18.

Fig. 16 is a diagram of a multiplex carrier telephone system including the channel modulating and demodulating equipment, the filter apparatus required for segregating the different channels and the amplifying apparatus at the terminals and at intermediate points along the line. In this figure voice-frequency currents derived from the instruments SS are applied to individual modulators, as indicated by CM, which convert them to carrier frequencies. The wanted sidebands are selected by channel filters CF and may, after passing through the amplifier TA, be applied to the line section LC comprising a wire with hexagonal shield return designed in accordance with the invention. At suitable points in the line repeaters such as IR may be inserted. At the receiving end the incoming carrier channels may, after being amplified in the receiving amplifier RA, be separated by means of the channel filters SF and be brought again to voice frequencies in channel demodulators as indicated by CD. The arrangement as shown serves for transmission in one di-

rection and a duplicate arrangement would be provided for the opposite direction of transmission.

Fig. 17 is a diagram of a television system in which the line circuit is provided by a circuit of hexagonal form. In this diagram TT represents the television transmitting apparatus by means of which the television signals are applied to the line circuit LC. The transmitting apparatus may be such as to furnish to the line a band of frequencies extending from approximately zero frequency to a high frequency determined by the degree of image definition which it is desired to obtain. If desired, however, this apparatus may also include modulating equipment whereby the television band of signals is shifted to a higher position in the frequency spectrum. At the receiving end the television receiving apparatus TR takes the band of signals delivered by the line and converts it into the desired image, this apparatus including whatever demodulating apparatus may be required to shift the frequency position of the television band in a manner reverse to that employed at the transmitting end. The arrangement illustrated serves for a single direction of transmission and may be duplicated for the opposite direction of transmission. It is obvious that other signals, as, for example, those from voice channels, may be combined with the television signals for transmission over the line.

Fig. 18 is a diagram of a radio transmitting system in which the connection from the transmitting apparatus to the transmitting antenna is secured by means of a circuit with double-hexagonal configuration and the connection between the receiving antenna and the receiving apparatus is similarly obtained. In this diagram RT designates radio transmitting apparatus and TL a transmission circuit for connecting this apparatus to the transmitting antenna TA, while RA designates a receiving antenna whose output is transmitted over the receiving circuit RL to the radio receiving apparatus RR. Where the antenna is balanced with respect to ground, the double-hexagonal type of circuit might be preferable. Where a connection is made between antenna and ground, however, the unbalanced single hexagonal type of circuit might be advantageous.

The terminal apparatus and amplifiers which may be used in connection with a transmission line such as previously described may be shielded from electrical interference from outside sources by surrounding them with sheet metal compartments. These compartments may be connected to the shield of the transmission line if desired. Such compartments are illustrated in Figs. 16, 17 and 18.

In the above description of circuits of double-hexagonal configuration it has been contemplated that balanced transmission would be employed with the conductors 1 and 2 serving one as a return for the other. If desired, it would be possible to derive from the same structure an independent transmission circuit by connecting the conductors 1 and 2 in parallel and using the shield as a return. Figs. 19 and 20 illustrate two different methods of deriving two independent transmission circuits, one balanced and one unbalanced, from a double-hexagonal structure as, for example, that shown in Fig. 13.

In Fig 19, the generator G_1 is connected to the conductors 1 and 2 through the transformer T_1 , thus providing a balanced to ground circuit. Generator G_2 is connected between the electrical midpoint of the conductors 1 and 2, provided by a

center tap on the secondary of transformer T₁ and the shield, providing a second circuit, the latter being unbalanced to ground. In Fig. 20, the electrical midpoint of conductors 1 and 2 is obtained by connecting two equal resistances R₁ and R₂ in series across the generator G₁. The generator G₂ is connected between the shield 3 and the junction of the two resistances R₁ and R₂.

It will be apparent that the types of transmission circuits and the types of structures afford a wide degree of flexibility with respect to the methods in which they may serve as transmission media.

Figs. 21 and 22 illustrate methods in which structures of the type shown in Figs. 6 to 15 may be laid up in cable form. In Fig. 22, the go and return conductors of each double-hexagonal circuit are shown connected by dotted lines. The double-hexagonal structures shown in Fig. 22 may or may not have a wall separating the two hexagons. In the lay-ups shown for the double-hexagonal type of circuit shown in Fig. 22 the various circuits are so disposed with reference to one another as to tend to minimize the coupling which would exist between them at low frequencies, where the shielding is only partially effective.

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

What is claimed is:

1. An electrical transmission circuit including a cylindrical conductor surrounded by and insulated from a conducting shield whose inner and outer surfaces are hexagonal and which is disposed coaxially with respect to the enclosed conductor, and terminal apparatus associated with said conductor for applying thereto and receiving and utilizing therefrom a band of signal frequencies whose range is many times that of the audible range, said conductor having its transmission characteristics so modified by said shield as to transmit without excessive attenuation the band of frequencies so applied.

2. An electrical transmission circuit derived from a structure which includes a cylindrical conductor surrounded by and insulated from a conducting shield whose inner and outer surfaces are hexagonal and which is disposed coaxially with respect to the enclosed conductor, the ratio of the inner diameter of said shield as measured between opposite corners of the hexagon to the outer diameter of said cylindrical conductor being slightly greater than

$$\frac{2}{\sqrt{3}} \frac{c_1}{b_1}$$

where b_1 is the radius of an inner conductor and c_1 the radius of the inner surface of a cylindrical outer conductor of a system designed for minimum attenuation in which the inner surface of the outer conductor is that of a cylinder inscribed within said hexagon.

3. An electrical transmission circuit comprising a cylindrical conductor surrounded by, insulated from and disposed coaxially with respect to a hexagonal outer conductor, said cylindrical conductor having a continuously conducting surface so that conduction of currents whose frequencies are substantially above the audible range takes place substantially on the surface of said cylindrical conductor, the ratio of the inner diameter

of said outer conductor as measured between opposite corners of the hexagon to the outer diameter of said cylindrical conductor being slightly greater than

$$\frac{2}{\sqrt{3}} \frac{c_1}{b_1}$$

where b_1 is the radius of an inner conductor and c_1 the radius of the inner surface of a cylindrical outer conductor of a system designed for minimum attenuation in which the inner surface of the outer conductor is that of a cylinder inscribed within said hexagon.

4. An electrical transmission circuit comprising a cylindrical conductor surrounded by, insulated from and disposed coaxially with respect to a hexagonal outer conductor, said cylindrical conductor consisting of a plurality of conducting strands insulated from one another, the ratio of the inner diameter of said outer conductor as measured between opposite corners of the hexagon to the outer diameter of said cylindrical conductor being slightly greater than

$$\frac{2}{\sqrt{3}} \frac{c_1}{b_1}$$

where b_1 is the radius of an inner conductor and c_1 the radius of the inner surface of a cylindrical outer conductor of a system designed for minimum attenuation in which the inner surface of the outer conductor is that of a cylinder inscribed within said hexagon.

5. An electrical transmission circuit comprising a cylindrical conductor surrounded by and disposed coaxially with respect to a hexagonal outer conductor, said cylindrical conductor and hexagonal outer conductor being insulated from one another by a substantially gaseous dielectric, and terminal apparatus associated with said conductor for applying thereto and receiving and utilizing therefrom a band of signal frequencies whose range is many times that of the audible range, said conductor having its transmission characteristics so modified by said shield as to transmit without excessive attenuation the band of frequencies so applied.

6. An electrical transmission circuit comprising two cylindrical conductors, one of said conductors being connected as a return for the other, a conducting shielding arrangement for said conductors having such configuration that each of said conductors is surrounded by and insulated from an inner shielding surface which is hexagonal and which is disposed coaxially with respect to the enclosed conductor, the transmission path formed from said cylindrical conductors acting one as a return for the other having connected thereto apparatus for applying thereto and utilizing therefrom a band of signal frequencies whose range is many times that of the audible range, the path formed by said conductors having its transmission characteristics so modified by said shield as to transmit without excessive attenuation the band of frequencies so applied.

7. An electrical transmission circuit comprising two cylindrical conductors, one of said conductors being connected as a return for the other, a conducting shielding arrangement for said conductors having such configuration that each of said conductors is surrounded by and insulated from an inner shielding surface which is hexagonal and which is disposed coaxially with respect to the enclosed conductor, said cylindrical conductors being of such a type that conduction

of currents whose frequencies are substantially above the audible range takes place substantially on the surface of said cylindrical conductors, the ratio of the inner diameter of said shield as measured between opposite corners of the hexagon to the outer diameter of said cylindrical conductor being slightly greater than

$$\frac{2}{\sqrt{3}} \frac{c_1}{b_1}$$

where b_1 is the radius of an inner conductor and c_1 the radius of the inner surface of a cylindrical outer conductor of a system designed for minimum attenuation in which the inner surface of the outer conductor is that of a cylinder inscribed within said hexagon.

8. An electrical transmission circuit comprising two cylindrical conductors, one of said conductors being connected as a return for the other, a conducting shielding arrangement for said conductors having such configuration that each of said conductors is surrounded by and insulated from an inner shielding surface which is hexagonal and which is disposed coaxially with respect to the enclosed conductor, said cylindrical conductors consisting of a plurality of conducting strands insulated from one another, the ratio of the inner diameter of said shield as measured between opposite corners of the hexagon to the outer diameter of said cylindrical conductor being slightly greater than

$$\frac{2}{\sqrt{3}} \frac{c_1}{b_1}$$

where b_1 is the radius of an inner conductor and c_1 the radius of the inner surface of a cylindrical outer conductor of a system designed for minimum attenuation in which the inner surface of the outer conductor is that of a cylinder inscribed within said hexagon.

9. An electrical transmission circuit comprising two cylindrical conductors, one of said conductors being connected as a return for the other, a conducting shielding arrangement for said conductors having such configuration that each of said conductors is surrounded by and insulated by a substantially gaseous dielectric from an inner shielding surface which is hexagonal and which is disposed coaxially with respect to the enclosed conductor, and terminal apparatus associated with said conductor for applying thereto and receiving and utilizing therefrom a band of signal frequencies whose range is many times that of the audible range, said conductor having its transmission characteristics so modified by said shield as to transmit without excessive attenuation the band of frequencies so applied.

10. An electrical transmission circuit comprising a cylindrical conductor surrounded by, insulated from and disposed coaxially with respect to a hexagonal outer conductor, one of said conductors being connected as a return for the other, the ratio of the inner diameter of said outer conductor, as measured between opposite corners of the hexagon, to the outer diameter of the inner conductor being slightly greater than

$$\frac{2}{\sqrt{3}} \frac{c_1}{b_1}$$

where b_1 is the radius of an inner conductor and c_1 the radius of the inner surface of a cylindrical outer conductor of a system designed for minimum attenuation in which the inner surface of the outer conductor is that of a cylinder inscribed within said hexagon.

11. An electrical transmission circuit comprising a cylindrical conductor surrounded by, insulated from and disposed coaxially with respect to a hexagonal outer conductor, one of said conductors being connected as a return for the other, the ratio of the inner diameter of said outer conductor, as measured between opposite corners of the hexagon, to the outer diameter of the inner conductor being approximately within the range between 3.8 and 5.0.

12. An electrical transmission circuit comprising a cylindrical conductor surrounded by, insulated from and disposed coaxially with respect to a hexagonal outer conductor, one of said conductors being connected as a return for the other, said cylindrical conductor being of such a type that conduction of currents whose frequencies are substantially above the audible range takes place substantially on the surface of said cylindrical conductor, the ratio of the inner diameter of said outer conductor, as measured between opposite corners of the hexagon, to the outer diameter of the inner conductor, being approximately 4.3.

13. An electrical transmission circuit comprising a cylindrical conductor surrounded by, insulated from and disposed coaxially with respect to a hexagonal outer conductor, one of said conductors being connected as a return for the other, said cylindrical conductor consisting of a plurality of conducting strands insulated from one another, the ratio of the inner diameter of said outer conductor, as measured between opposite corners of the hexagon, to the outer diameter of the inner conductor being approximately within the range between 3.8 and 5.0.

14. An electrical transmission circuit comprising a cylindrical conductor surrounded by, insulated by a substantially gaseous dielectric from, and disposed coaxially with respect to a hexagonal outer conductor, one of said conductors connected as a return for the other, the ratio of the inner diameter of the said outer conductor, as measured between opposite corners of the hexagon, to the outer diameter of the inner conductor being approximately within the range between 3.8 and 5.0.

15. An electrical transmission circuit comprising two cylindrical conductors, one of said conductors being connected as a return for the other, a conducting shielding arrangement for said conductors having such configuration that each of said conductors is surrounded by and insulated from an inner shielding surface which is hexagonal and which is disposed coaxially with respect to the enclosed conductor, the ratio of the inner diameter of said shield as measured between opposite corners of the hexagon to the outer diameter of said cylindrical conductor being slightly greater than

$$\frac{2}{\sqrt{3}} \frac{c_1}{b_1}$$

where b_1 is the radius of an inner conductor and c_1 the radius of the inner surface of a cylindrical outer conductor of a system designed for minimum attenuation in which the inner surface of the outer conductor is that of a cylinder inscribed within said hexagon.

16. An electrical transmission circuit comprising two cylindrical conductors, one of said conductors being connected as a return for the other, a conducting shielding arrangement for said conductors having such configuration that each of said conductors is surrounded by and insulated

from an inner shielding surface which is hexagonal and which is disposed coaxially with respect to the enclosed conductor, the ratio of the inner diameter of each shielding surface, as measured between opposite corners of the hexagon, to the outer diameter of the enclosed conductor being approximately in the range between 3.8 and 5.0.

17. An electrical transmission circuit comprising two cylindrical conductors, one of said conductors being connected as a return for the other, a conducting shielding arrangement for said conductors having such configuration that each of said conductors is surrounded by and insulated from an inner shielding surface which is hexagonal and which is disposed coaxially with respect to the enclosed conductor, each of said conductors being of such a type that conduction of currents whose frequencies are substantially above the audible range takes place substantially on the surface of said cylindrical conductors, the ratio of the inner diameter of each shielding surface, as measured between opposite corners of the hexagon, to the outer diameter of the enclosed conductor being approximately 4.3.

18. An electrical transmission circuit comprising two cylindrical conductors, one of said conductors being connected as a return for the other, a conducting shielding arrangement for said conductors having such configuration that each of said conductors is surrounded by and insulated from an inner shielding surface which is hexagonal and which is disposed coaxially with respect to the enclosed conductor, said cylindrical conductors consisting of a plurality of conducting strands insulated from one another, the ratio of the inner diameter of each shielding surface, as measured between opposite corners of the hexagon, to the outer diameter of the enclosed conductor being approximately within the range between 3.8 and 5.0.

19. An electrical transmission circuit comprising two cylindrical conductors, one of said conductors being connected as a return for the other, a conducting shielding arrangement for said conductors having such configuration that each of said conductors is surrounded by an inner shielding surface which is hexagonal and which is disposed coaxially with respect to the enclosed conductor, said cylindrical conductors being insulated from said shielding arrangement by a substantially gaseous dielectric, the ratio of the inner diameter of each shielding surface, as measured between opposite corners of the hexagon, to the outer diameter of the enclosed conductor being approximately within the range between 3.8 and 5.0.

20. An electrical transmission circuit comprising two cylindrical conductors, one of said conductors being connected as a return for the other, a conducting shielding arrangement for said conductors having such configuration that each of said conductors is surrounded by and insulated from an inner shielding surface which is hexagonal and which is disposed coaxially with respect to the enclosed conductor, means for connecting said conductors in series to form a transmission circuit, the transmission path formed from said cylindrical conductors acting one as a return for the other having connected thereto apparatus for applying thereto and utilizing therefrom a band of signal frequencies whose range is many times that of the audible range, the path formed by said conductors having its transmission characteristics so modified by said shield as to transmit without excessive attenuation the band of frequencies so applied, and means for connecting to the electrical center of the said pair of conductors for establishing an independent transmission circuit between said pair of conductors in parallel as one conductor and said shielding arrangement as the other conductor.

21. A plurality of electrical transmission structures arranged to form a cable, each of said structures comprising two cylindrical conductors, one of said conductors being connected as a return for the other to form a transmission circuit, a conducting shielding arrangement for said conductors having such configuration that each of said conductors is surrounded by and insulated from an inner shielding surface which is hexagonal and which is disposed coaxially with respect to the enclosed conductor, the transmission path formed from said cylindrical conductors acting one as a return for the other having connected thereto apparatus for applying thereto and utilizing therefrom a band of signal frequencies whose range is many times that of the audible range, the path formed by said conductors having its transmission characteristics so modified by said shield as to transmit without excessive attenuation the band of frequencies so applied, said structures being arranged in such a manner as to tend to minimize the electrical interference between said circuits.

22. A plurality of electrical transmission structures arranged to form a substantially cylindrical cable, each of said structures comprising a cylindrical conductor surrounded by and insulated from a conducting shield whose inner and outer surfaces are hexagonal and which is disposed coaxially with respect to the enclosed conductor.

ESTILL I. GREEN.