

June 25, 1968

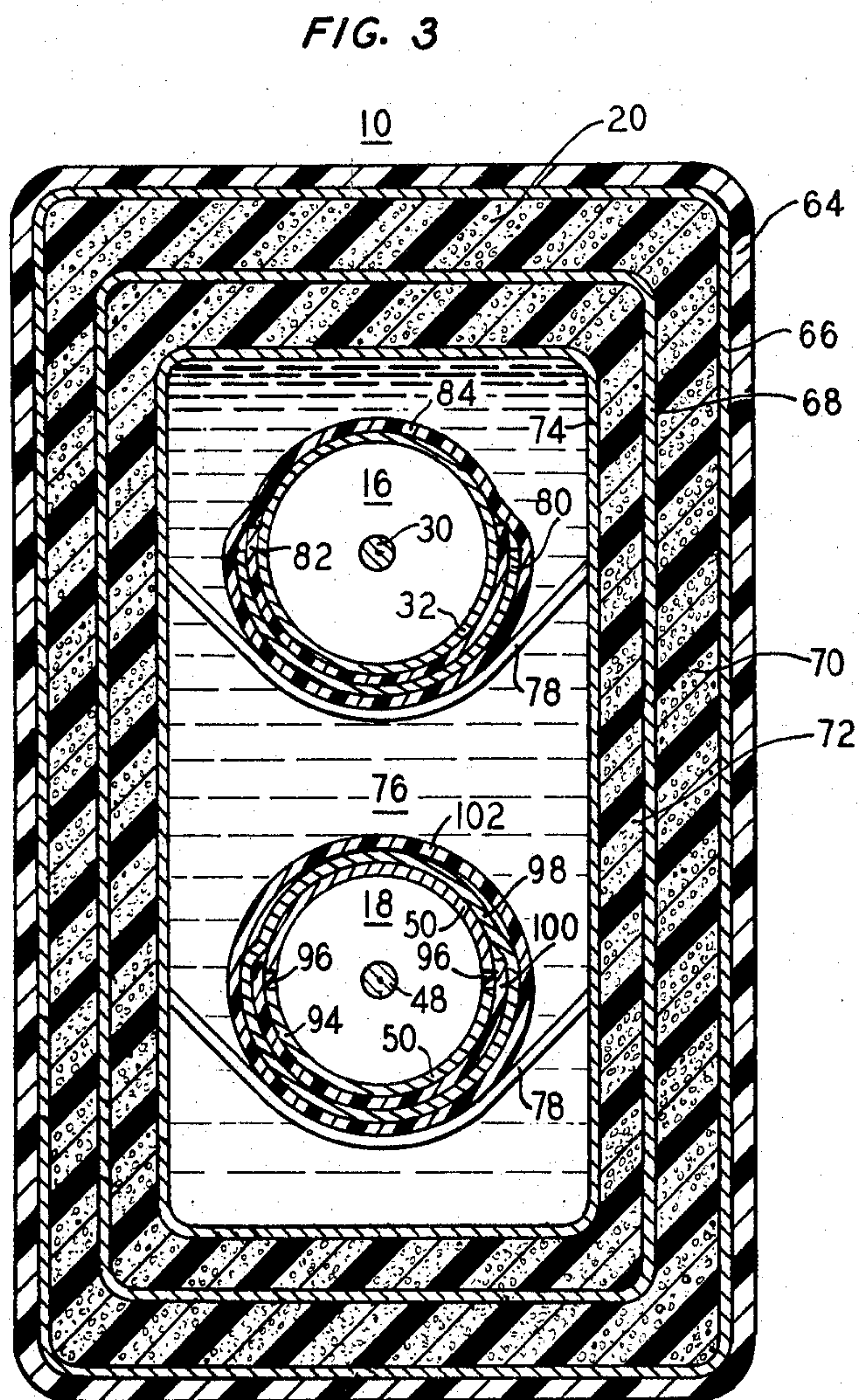
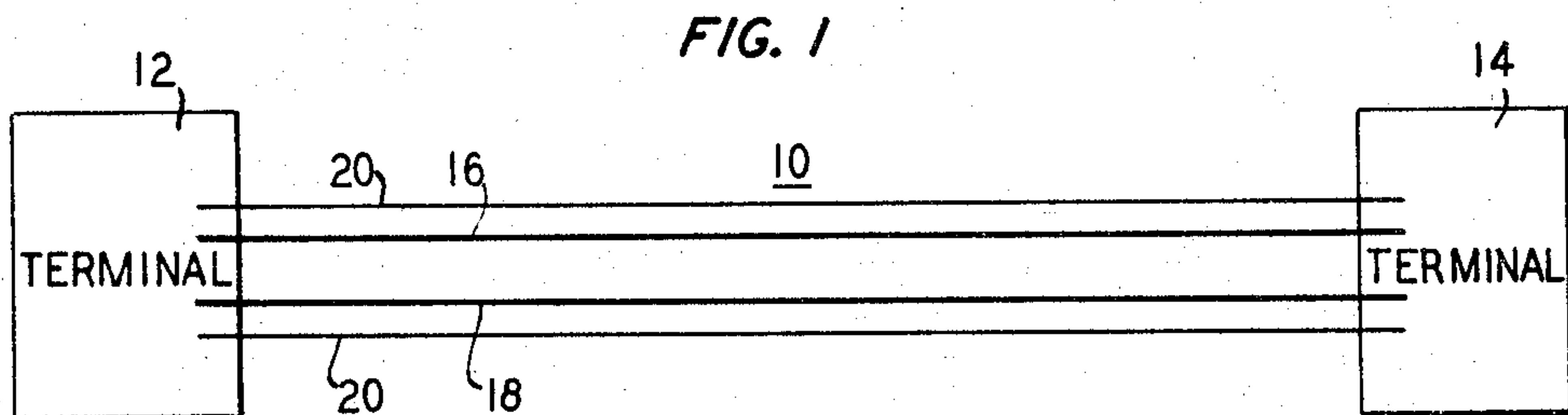
D. J. THOMSON

3,390,357

LOW-LOSS COMMUNICATIONS CABLE

Filed Dec. 29, 1966

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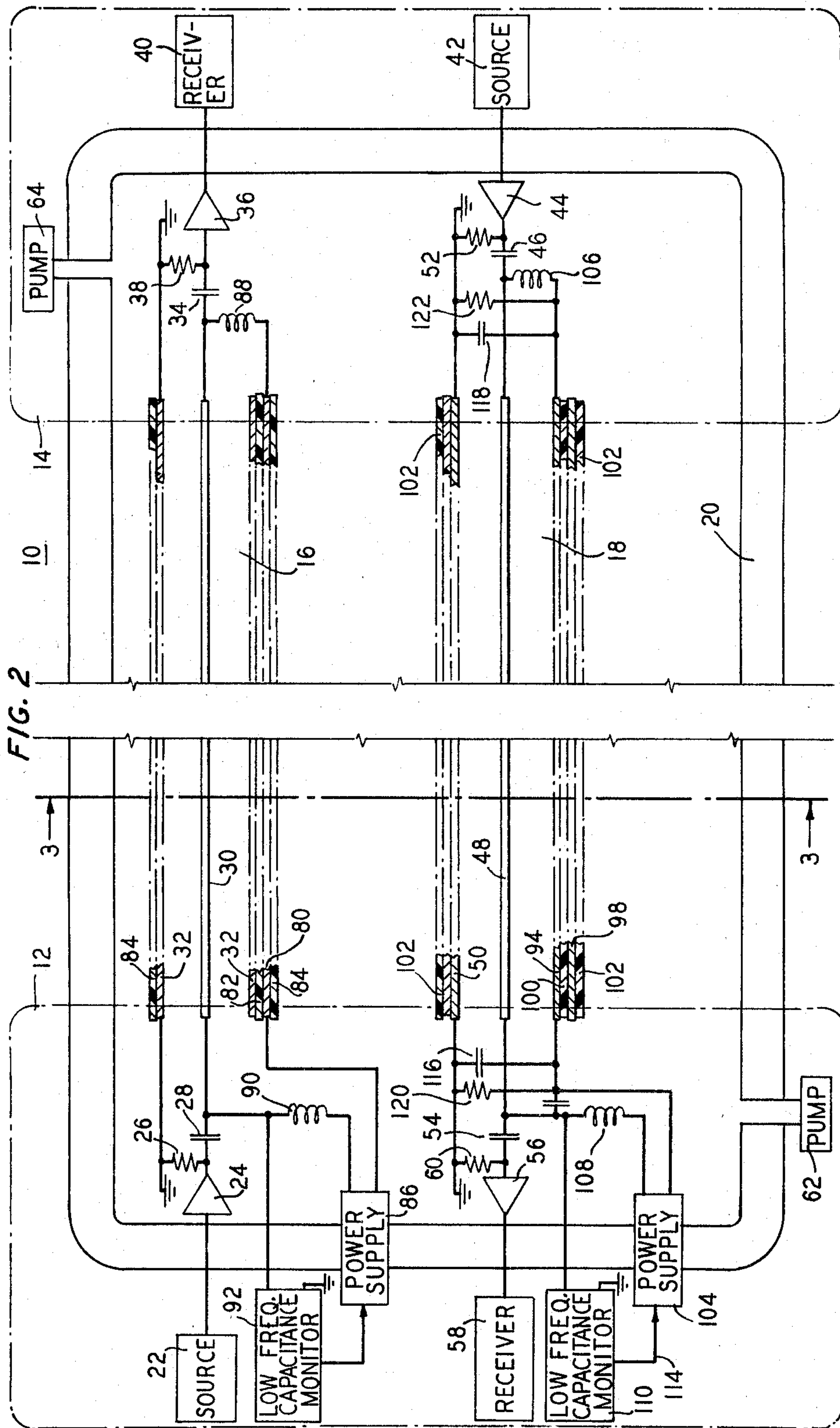
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FIG. 4

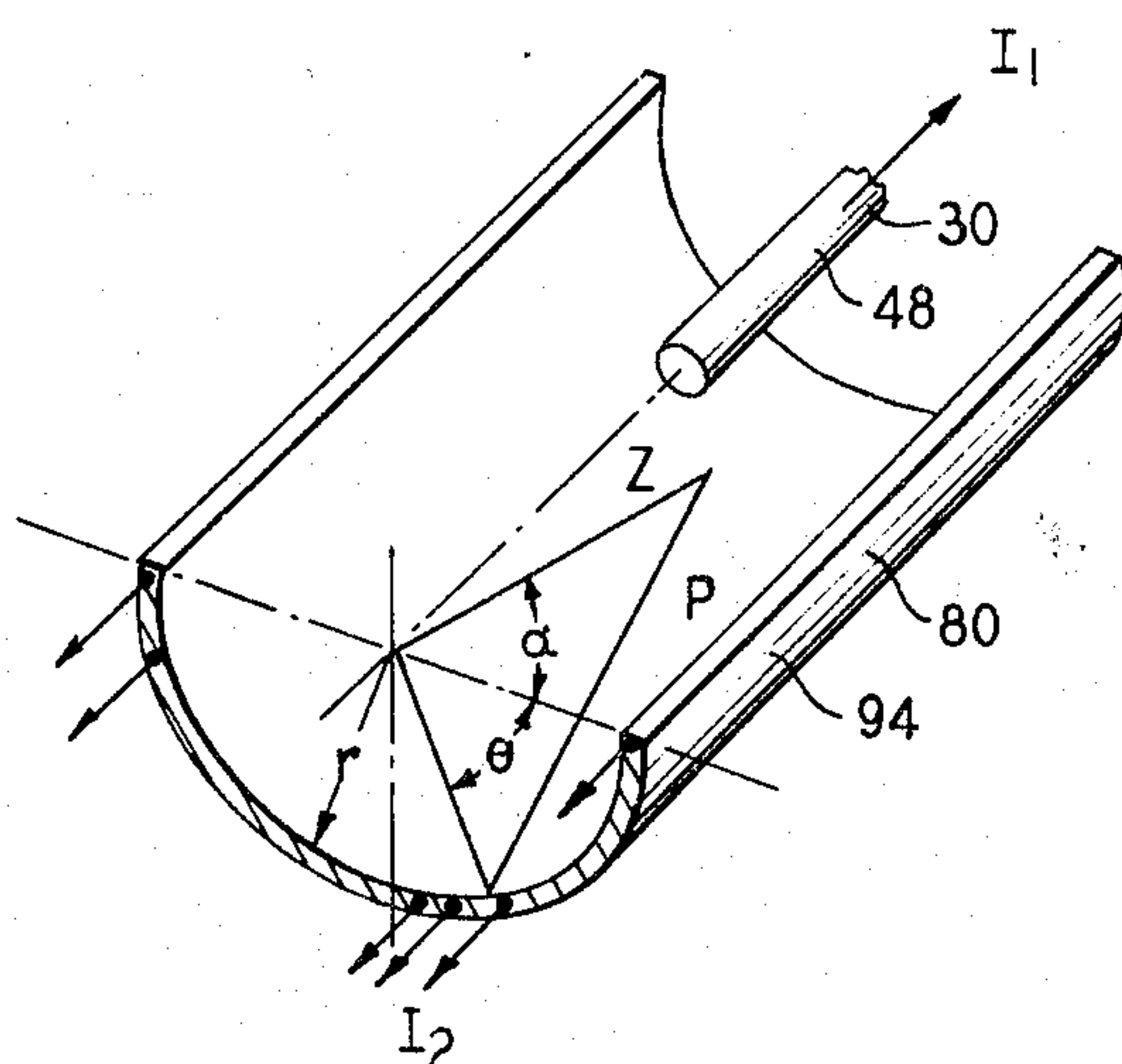
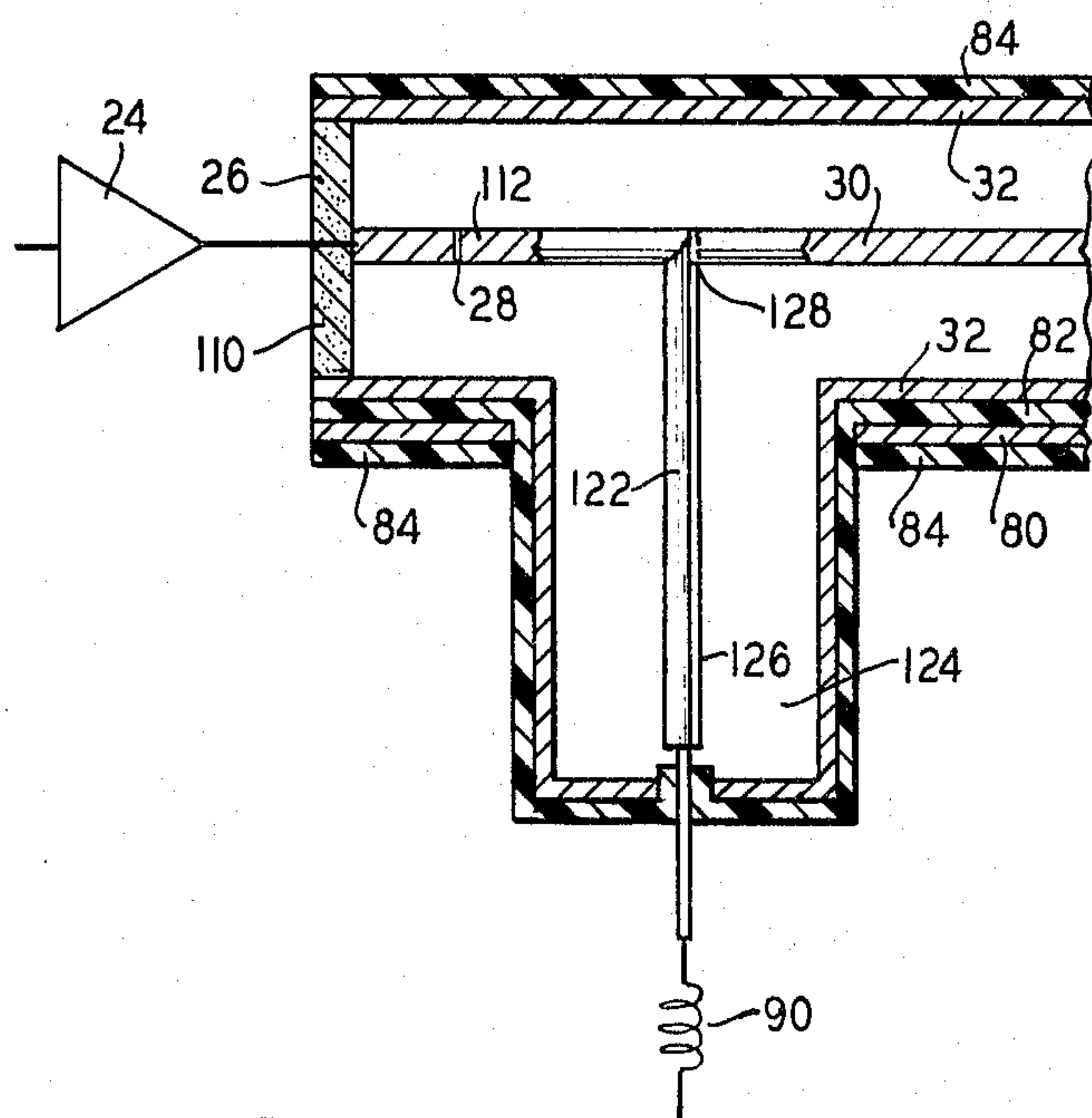


FIG. 5



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LOW-LOSS COMMUNICATIONS CABLE

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16 Claims. (Cl. 333-17)

ABSTRACT OF THE DISCLOSURE

A longitudinal superconducting semicylinder arranged coaxially near the outer conductor of a coaxial cable and maintained with the cable at cryogenic temperature, carries a current that forms a magnetic field which supports the cable's superconducting center conductor coaxially within the outer conductor, when the center conductor carries an opposing current. Solid dielectrics between the coaxial conductors are not necessary. Thus, dielectric losses are eliminated.

Background of the invention

This invention relates to electrical cable transmission systems, particularly those incorporating coaxial cables for transmitting high frequency signal components.

In a coaxial cable, a solid dielectric coaxially supports a center conductor within a surrounding tubular conductor and electrically separates the two. The solid dielectric may be longitudinally continuous. On the other hand, it may consist of longitudinally spaced discs surrounding the center conductor. In either case the dielectric, because of its high dielectric constant or frequency-dependent dispersions in its dielectric constant and lack of uniformity, exhibits losses and reflections, and hence introduces noticeable distortions to high frequency signals passing through the cable. The intermittent disc-spaced cables were originally developed to minimize these distortions and takes advantage of the low dielectric constant of air between the inner and outer conductors. However, any lack of uniformity between successive discs produces signal distortions which accumulate undesirably.

The invention

The invention minimizes these deficiencies, by the feature of eliminating altogether the solid dielectric between the cable ends, and passing, along a path symmetrically below the center conductor and back through the center conductor, currents that form magnetic fields sufficient to coaxially support the center conductor. This affords the space between conductors the most uniform and lowest possible dielectric constant. Preferably the high currents necessary for establishing the conductor-supporting field are achieved by forming the path and its return from superconducting materials maintained at a cryogenic temperature. Additional limitations of the cable, namely losses introduced by the resistance of the conductors, are also minimized according to the invention by similarly forming the conductors from superconducting materials and simultaneously maintaining these at cryogenic temperatures.

According to a particular feature of the invention the support current carrying path is cross-sectionally semicircular and arranged coaxially about the lower half section of the outer conductor. According to an alternate feature, the cross-sectionally semicircular path comprises a portion of the outer conductor.

These and other features of the invention are pointed out in the claims. Other objects and advantages of the invention will appear from the following detailed description when read in light of the accompanying drawings.

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The drawings

In the drawings:

FIG. 1 is an elevation schematically showing a cable system embodying features of the invention;

FIG. 2 is a partly schematic elevation showing details of the embodiment in FIG. 1;

FIG. 3 is a section 3-3 of FIG. 2;

FIG. 4 is a perspective view of a portion of the cable in FIGS. 2 and 3 for explaining its operation; and

FIG. 5 is a schematic sectional elevation showing details of the embodiment of FIG. 2.

Description of preferred embodiment

In FIGS. 1 and 2, a coaxial cable system 10 joins two terminals 12 and 14 for transmitting high frequency signals between them. The terminals 12 and 14 may, for example, be computer elements or they may be telephone central offices in distant cities. In the cable system 10, two superconducting cable coaxials 16 and 18 connect the circuits of the terminals 12 and 14. Surrounding the coaxials 16 and 18 and portions of the terminals 12 and 14 is a cooling jacket 20 filled with liquid helium for maintaining the system 10 and the terminal portion at cryogenic temperatures.

High frequency signals such as telephone carrier or high-speed computer signals generated by a source 22 outside the cooling jacket 20 in the terminal 12 are amplified in a cryogenically cooled isolation amplifier 24 which is terminated by a grounded impedance-matching resistor 26. A blocking capacitor 28 passes the signals so they appear across the superconducting center conductor 30 and the grounded superconducting outer conductor 32 of the coaxial 16. The coaxial transmits these signals to the terminal 14. A blocking capacitor 34 in the terminal 14 at the other end of line 16 passes the signals to the input of a cryogenically cooled isolation amplifier 36 also in the terminal 14. A loading resistor 38 adjusts the input impedance of the amplifier 36 to match the characteristic impedance of line 16 and thereby minimize reflections. The signals amplified by the isolation amplifier 36 pass through the jacket 20 to a receiver 40 in the uncooled portion of terminal 14.

The terminal 14 also has a signal source 42. Telephone carrier, computer or other high frequency signals generated here, after amplification by a cryogenically cooled isolation amplifier 44, are coupled by a blocking capacitor 46 across the superconducting center conductor 48 and the superconducting outer conductor 50 of the coaxial 18. These signals are transmitted by the coaxial 18 to the terminal 12. A grounded resistor 52 matches the impedances of the amplifier 44 and the coaxial 18. A blocking capacitor 54 couples the other end of the coaxial 18 in the terminal 14 to an isolation amplifier 56. The latter furnishes isolated and strengthened signals through the jacket 20 to a receiver 58. A grounded resistor 60 matches the impedance of amplifier 56 to that of coaxial 18.

Suitable pumps 62 and 64 in the respective terminals 12 and 14 fill the jacket 20 with liquid helium. Suitable means not shown in FIG. 2 cap the ends of the coaxials 16 and 18 so as to prevent entry of refrigerant.

Cross-sectional details of the cable system of FIGS. 1 and 2 appear in FIG. 3. Here in the jacket 20 an outer sleeve 64 of plastic material such as polyethylene surrounds a protective lightning-absorbing shield 66 of metal such as aluminum. Separating the shield 66 from a redundant metal shield 68 is a water-resistant insulating layer 70 of material such as polyurethane foam. A heat-insulating layer 72 of material such as polyurethane foam under the shield 68 is protected on the inside by a third metal shield 74. The chamber formed by the shield 74 is filled with a liquid gas 76 such as liquid helium for

producing cryogenic temperatures. Straps 78 of material such as aluminum suspend the coaxials 16 and 18 in the chamber within the shield 74.

According to the invention the center conductor 30 in the coaxial 16 is maintained in its central position by means of current carried longitudinally by a semicircular cross-sectioned superconducting support conductor 80 placed coaxially below the cylindrical outer conductor 32 and separated therefrom by a dielectric layer 82 of a material such as polyethylene. A nonconductive layer 84 such as of plastic material surrounds the entire coaxial. As shown in FIG. 2 power for the support conductor 80 comes from a power supply 86. This, for example, is a thermocouple that is energized by placing one portion inside and one portion outside the jacket 20. In FIG. 2 its direct current output flows through the superconducting cryogenic-temperature support conductor 80 at a value of hundreds of amperes, longitudinally along the coaxial 16 to a high-frequency-choking inductor 88. The latter keeps the power supply from shorting the high frequency signals on the center conductor 30. It passes the direct support current back to terminal 12 through the center conductor 30. In the terminal 12, a high-frequency-choking inductor 90 passes the high support current by to the supply 86. In both terminals 12 and 14 the blocking capacitors 28 and 34 prevent the support current from affecting the incoming and outgoing signal voltages.

The magnitude of the voltage for maintaining the center conductor 30 centrally located is controlled by a low frequency capacitance monitor 92. The latter measures the capacitance between the center conductor 30 and the outer conductor 32. That capacitance is minimum when the center conductor is centrally located. The capacitance monitor keeps adjusting the power supply to obtain a minimum capacitance. When the power supply 86 is a thermocouple it can do this by varying the current in a heating coil that heats the hot side of the thermocouple.

The structure of the coaxial 18 differs from that of coaxial 16 in that a superconducting support conductor 94 forms part of the outer conductor 50. This appears most obviously in FIG. 3. Here the conductor 50 is split longitudinally by two dielectric spacers 96 made, for example, of polyethylene. This keeps the direct support current in the lower part. However, a superconducting conductive layer 98 contacting the upper part of conductor 50 couples capacitively to the support conductor across a dielectric layer 100. The latter covers the support conductor 94 and portions of the upper part adjacent the spacers 96. A protective insulating layer 102 embraces the entire coaxial 18.

To furnish support current to the conductor 94 a direct power supply 104 corresponding to power supply 86 passes direct current along the conductor 94 to the other end of coaxial 16 at terminal 14. There a high-frequency-choking inductor 106 passes the direct current through the center conductor 48 back to the terminal 12. Another high-frequency-choking inductor 108 in terminal 12 returns the support current to the power supply. Blocking capacitors 46 and 54 prevent the support current from affecting the amplifiers 44 and 54.

Similar to the case with the coaxial 16 a low frequency capacitance monitor 110 corresponding to the monitor 92 measures the capacitance of the center conductor 48 through a line 112 relative to the grounded outer conductor 50. It regulates the power supply 104 through line 114. It attempts to maintain a minimum capacitance. This minimum capacitance occurs when the center and outer conductors 48 and 50 are coaxial.

Supplemental capacitors 116 and 118 at the ends of the coaxial 18 and across the conductors 50 and 94 add capacitive coupling between these two parts. An excessive charge between these parts is prevented by bleeder resistors 120 and 122 across the capacitors 116 and 118, respectively.

To take full advantage of the cryogenic temperatures

afforded by the liquid helium the conductors 30, 32, 80, 48, 50 and 98 are preferably made from a superconducting material such as a niobium-zirconium alloy.

In operation the current generated by the power supplies 86 and 104 are very high despite low voltages because of the negligible impedances of the cryogenic temperature conductors. Their effects on the center conductors 30 and 48 are shown in FIG. 4. Here for simplicity only the center conductor corresponding to both conductors 30 and 48 and the support conductor corresponding to and designated conductors 94 and 80 are shown. A current I_1 passes through the center conductor 30. An opposing current I_2 passes through the support conductor 94. When the conductors are coaxially arranged, a vertical force

$$F_{v0} = \frac{\mu_0 I_1 I_2}{\pi^2 r}$$

holds up the center conductor, where r is the radius of the outer conductor and the radius of the center conductor is small; and when μ_0 is the magnetic permeability of free space, namely $4\pi \times 10^{-7}$.

If $I_1 = I_2$,

$$F_{v0} = \frac{\mu_0}{\pi} \frac{1}{r} \left(\frac{I}{\sqrt{\pi}} \right)^2 \text{ newton/m.}$$

The current necessary for vertically holding a center conductor of uniform mass M in kg./m. is

$$I_s = \pi \sqrt{\frac{M \cdot g \cdot r}{\mu_0}} \text{ amp.}$$

where g is the force of gravity.

If the center conductor is displaced from the geometric center to a point located by the polar coordinates (z, α) , any portion of the center conductor experiences a vertical force component

$$F_v = \frac{\mu_0 I^2}{2\pi \pi r} \int_0^\pi \frac{r \sin \theta + z \sin \alpha}{r^2 + z^2 - 2rz \cos(\alpha + \theta)} d\theta$$

where θ defines any point on the circumference of conductors 80, 94. This integral is equal to

$$F_v(z, \alpha) = \frac{\mu_0 I^2}{2\pi \pi r} \left\{ \frac{\pi \sin \alpha}{2rz} + \frac{\cos \alpha}{2z} \ln \left[\frac{r^2 + z^2 + 2rz \cos \alpha}{r^2 + z^2 - 2rz \cos \alpha} \right] + \frac{\sin \alpha}{(r^2 - z^2)} \left[\frac{r^2 + z^2}{2rz} - z \right] \sin^{-1} \left(\frac{(2rz)^2 + (r^2 + z^2)(2rz \cos \alpha + \sin \alpha)}{2rz(r^2 + z^2 + 2rz \cos \alpha)} \right) - \sin^{-1} \left\{ \frac{(2rz)^2 - (r^2 + z^2)(2rz \cos \alpha + \sin \alpha)}{2rz(r^2 + z^2 - 2rz \cos \alpha)} \right\} \right\}$$

Here the vertical force component is represented by an even symmetrical function with a minimum at $(0, 0)$.

On the other hand, when the center conductor is displaced from the geometric center to the point (z, α) any portion of the center conductor experiences a horizontal force component

$$F_h = \frac{\mu_0 I^2}{2\pi^2 r} \int_0^\pi \frac{r \cos \theta - z \cos \alpha}{r^2 + z^2 - 2rz \cos(\alpha + \theta)} d\theta$$

This is equal to

$$F_h(z, \alpha) = \frac{\mu_0 I^2}{2\pi \pi r} \left\{ \frac{\pi \cos \alpha}{2z} + \cos \alpha \left[r - \frac{r^2 + z^2}{2z} \right] \left[\sin^{-1} \left\{ \frac{(2rz)^2 + (r^2 + z^2)(2rz \cos \alpha + \sin \alpha)}{2rz(r^2 + z^2 + 2rz \cos \alpha)} \right\} - \sin^{-1} \left\{ \frac{(2rz)^2 - (r^2 + z^2)(2rz \cos \alpha + \sin \alpha)}{2rz(r^2 + z^2 - 2rz \cos \alpha)} \right\} \right] + r \sin \alpha \ln \left[\frac{r^2 + z^2 + 2rz \cos \alpha}{r^2 + z^2 - 2rz \cos \alpha} \right] \right\}$$

Thus the vertical and horizontal force components on the center conductor are represented by respective even and odd symmetrical functions F_v and F_h . The even func-

tion F_v is minimum at (0, 0). The odd function is 0 at (0, 0). The resultant force therefore acts to restore the center conductor to the point (0, 0). The mathematical basis for this conclusion is available from texts on classical mechanics such as "Classical Mechanics" by Herbert Goldstein published by the Addison-Wesley Co., 1965 edition, particularly on pages 318 to 321.

The current necessary to support the center conductor is high. For example 390 amps are needed for a niobium alloy cable of inner and outer radii, .125 and .475 cm., respectively. The necessary low series resistance is obtained by cooling to very low, such as cryogenic superconducting, temperatures.

Low temperature operation with extreme conductor conductivity furnishes low thermal noise and small attenuation and phase distortion in the transmission media.

The invention avoids the severe echoes which arise at pulse lengths of less than 1 ns., from the use of a disc dielectric because of impedance nonuniformities caused by variations in disc thickness. It also avoids the effects of solid dielectrics which give rise to distortions similar to that caused by skin effect in addition to adding shunt conductivity to the line.

The invention contemplates various details for operating the system of FIG. 2 most efficiently. An example of details for obtaining efficient operation of the schematically shown components and coaxial members 24, 26, 28 are related as shown in FIG. 5. These details are only examples. Other details are possible within the scope of the invention. The details apply also to the counterparts of these members at both ends of the line. In the example of FIG. 5, resistor 26 constituting a resistive disc 110, such as of graphite, caps the end of the coaxial 16. It thus serves not only as a resistor but also to prevent entry of the refrigerant into the coaxial. The disc 110 supports at its center a superconductive stub 112 that includes the capacitor 28. The stub terminates in a superconductive downwardly extending arm 122 that extends into the hollow of a T-connection 124 at the end of outer conductor 32. Slidably embracing and contacting a dovetail 126 on the side of the arm 122 is a bifurcated dovetail holder 128 that terminates the conductor 30.

The arm 122 helps the initial start-up action of this device. For example, at ordinary ambient temperatures the insulated center conductor may slide down the dovetail 126 and rest on the outer conductor 32. As cryogenic temperatures are reached, and current through the conductors 80 and 30 are great enough, the magnetic force lifts the center conductor 30 into the position shown. The arm 122 and holder 128 maintain the necessary contact for passing direct current.

The invention contemplates adopting structures similar to FIG. 5 for the coaxial 18, for example, by mounting a disc representing the resistor 60 between the conductor 94 and the top of conductor 50 to cap the coaxial. For initially lifting the center conductor 48 off the conductor 94, wide auxiliary conductors connected to the conductor 94 and extending across the T-connector are usable. These are held parallel to and below the conductor 48. They form a short direct-current loop with conductor 48 from the power supply. The magnetic field of the loop current first lifts one end of the dovetailed conductor 48 at the arm 122. This lifting forms a longer current loop. The rest of the conductor 48 then is lifted into position by currents flowing through the auxiliary conductor, the support conductor 94 and the center conductor 48.

According to the invention the support conductors 80 and 94 may have shapes other than that shown. The invention contemplates conductors of any shape that form symmetrical conducting paths vertically below the axes of the respective outer conductors 32 and 50 and extending far enough to the sides to prevent the center conductor from falling sideways. In FIGS. 2 and 3 the coaxials 16 and 18 are arranged vertically so that each may take advantage of the vertical force afforded by the other's

support conductor. Additional coaxials, or just a single coaxial may be used.

While embodiments of the invention have been disclosed in detail, it will be obvious to those skilled in the art that the invention may be embodied otherwise without departing from its spirit and scope.

What is claimed is:

1. An electric cable system comprising center conducting means, outer conducting means surrounding said center conducting means and having support conducting means located symmetrically below the geometric axis of said outer conducting means, electrical means for passing a current longitudinally through said support conducting means and back through said center conducting means, low temperature generating means surrounding said outer conducting means for maximizing the current flow through said conducting means whereby said support conducting means when carrying current applies a magnetic force to said center conducting means for maintaining said center conducting means in the geometric axis of said outer conducting means.

2. A system as in claim 1 wherein capacitance monitor means measure the capacitance between said center and outer conductors and control said electrical means for obtaining minimum capacitance measurements.

3. A system as in claim 1 wherein said support conducting means have a longitudinally continuous semi-circular cross section.

4. A system as in claim 1 wherein said cooling means include cryogenic refrigerating means.

5. A cable as in claim 1 wherein said cooling means include a heat-insulating jacket and pumping means for maintaining a liquid gas in said jacket.

6. A system as in claim 1 wherein said power supply includes thermocouple means partially refrigerated by said cooling means.

7. A system as in claim 1 further comprising source means for generating signals at one end of said center and outer conducting means and receiver means for receiving signals at the other end of said center and outer conducting means.

8. A system as in claim 7 further comprising filter means connected to said electrical means and said source means and said receiving means for keeping the current generated by said electrical means out of said source means and receiving means.

9. A system as in claim 1 wherein said outer conducting means comprises a cross-sectionally circular integral conducting tube and said support conducting means are located below said tube, insulating means separating said support conducting tube from said tube, and insulating means surrounding said outer conducting means for securing said tube and said support conducting means together.

10. A system as in claim 9 wherein said support conducting means have a longitudinally continuous semicircular cross section.

11. A system as in claim 1 wherein said outer conducting means comprise a tubular structure diametrically split into two portions, insulating means separating said portions, and capacitive means for coupling said portions, said lower portion forming said support conducting means.

12. A system as in claim 11 wherein said capacitive means comprise conductive means surrounding both portions and contacting said upper portions, and dielectric means separating said lower portion from said upper portion.

13. A system as in claim 12 further comprising second center conducting means, second outer conducting means having second support conducting means, all within said cooling means and having axes arranged vertically with respect to said first outer conductor means.

14. A system as in claim 13 wherein said second outer conducting means comprises an integral tubular structure of conductive material and having below it said support conductor means.

15. A system as in claim 1 further comprising high frequency generating means for passing high frequency currents through said center conducting means and said outer conducting means, and filter means for separating the effects of said electrical means from said generating means.

16. A system as in claim 1 further comprising means for contacting said center conductor means at positions away from its center position, said means including a T-connection.

References Cited

UNITED STATES PATENTS

3,327,265 6/1967 Van Geuns et al. ---- 335—216

OTHER REFERENCES

Forces Acting on Superconductors in Magnetic Fields, Journal of Applied Physics, vol. 24, No. 1, January 1953, pp. 19-24.

Shoenberg: Superconductivity, Cambridge Monographs on Physics, pp. 19-24.

The Cryogyro, Machine Design Engineering News, Feb. 4, 1960, pp. 14-15.

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