June 25, 1968 D. J. THOMSON 3,390,357

LOW-LOSS COMMUNICATIONS CABLE

Filed Dec. 29, 1966 3 Sheets-Sheet 1

FIG. 1

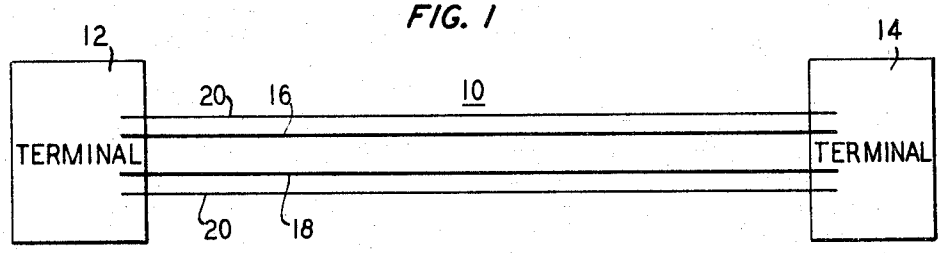
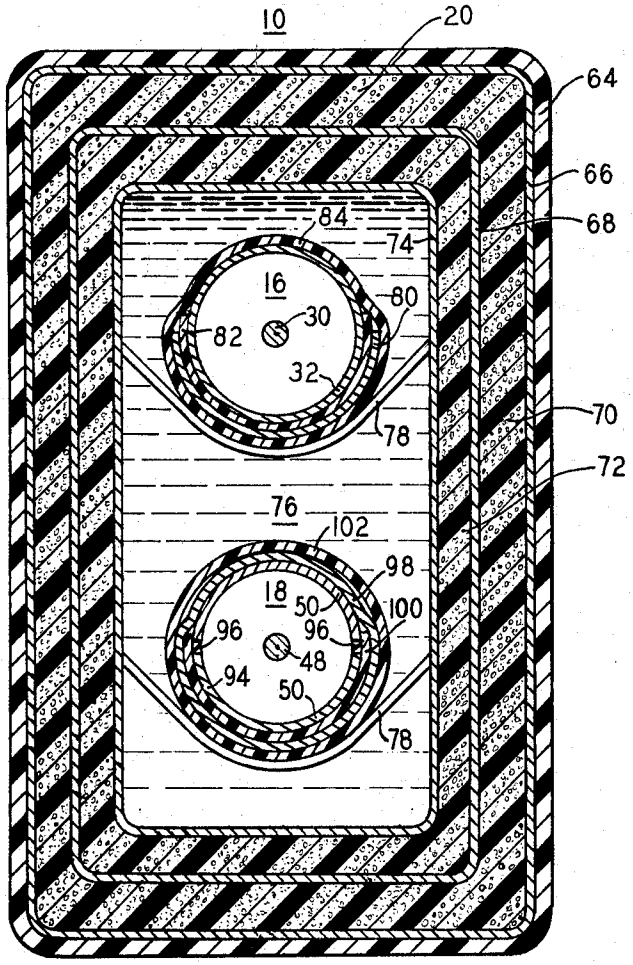


FIG. 3



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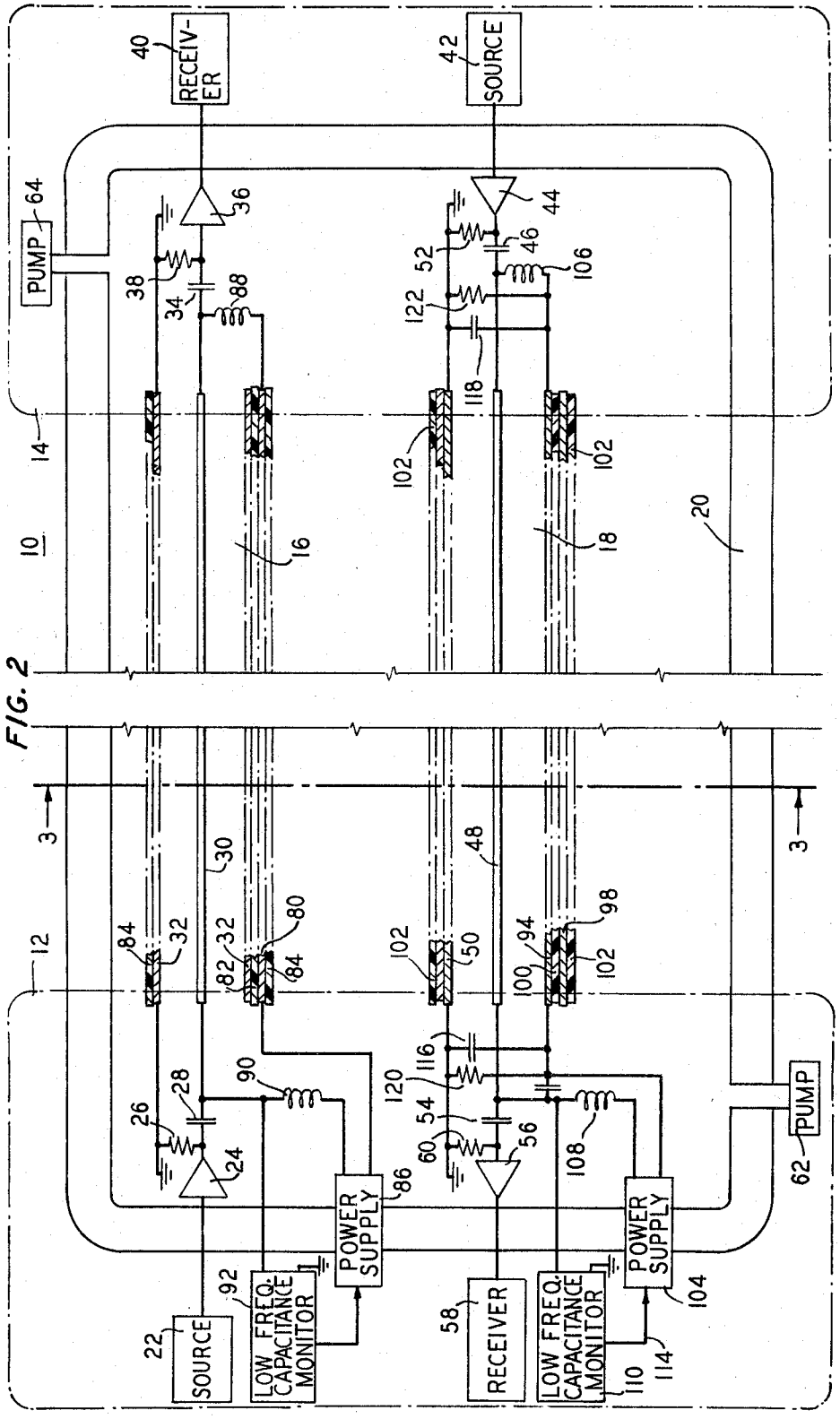


FIG. 2

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FIG. 4

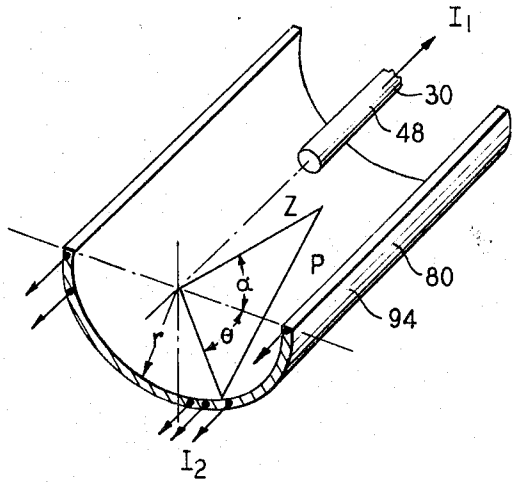
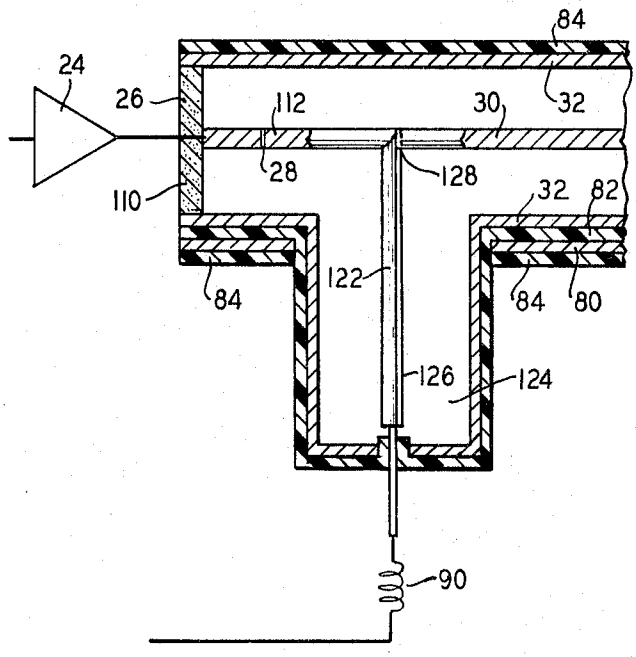


FIG. 5



United States Patent Office 3,390,357 Patented June 25, 1968

3,390,357

LOW-LOSS COMMUNICATIONS CABLE

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Filed Dec. 29, 1966, Ser. No. 605,922
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 urrent. 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.

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 offies 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 $4\pi\times10^{-7}$.

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

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

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

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

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

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

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

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

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 semicircular 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.

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