Dec. 31, 1946. M. J. DI TORO 2,413,607

TIME DELAY NETWORK

Filed March 12, 1945

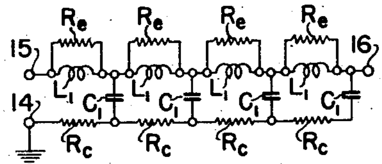

FIG.2

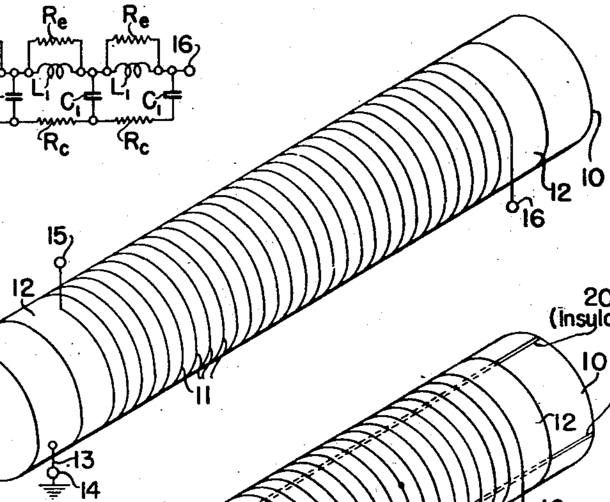

FIG.1

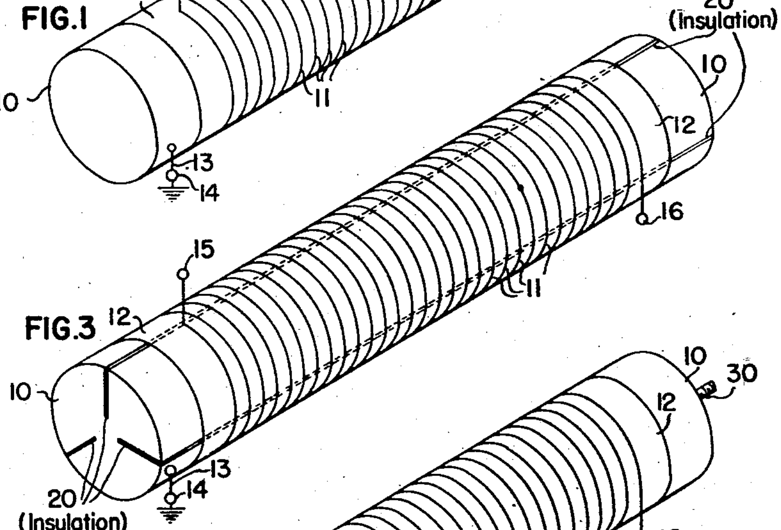

FIG.3

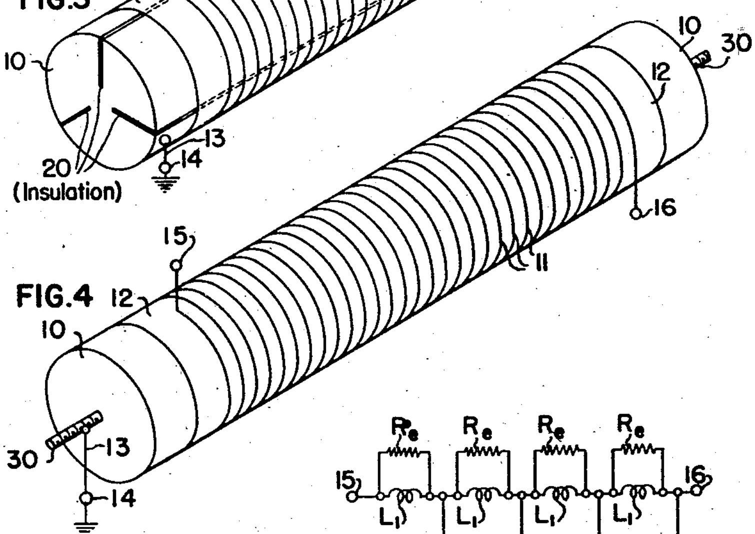

FIG.4

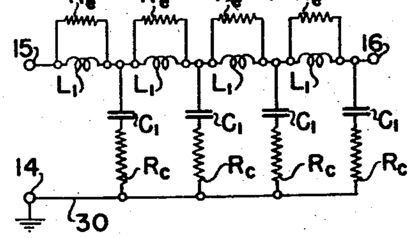

FIG.5

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TIME-DELAY NETWORK

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Application March 12, 1945, Serial No. 582,283

6 Claims. (Cl. 178—44)

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This invention is directed to time-delay networks of the unbalanced or three-terminal type for translating signal components included within a predetermined range of frequencies. It is related to the delay networks disclosed in copending applications Serial No. 582,285, filed March 12, 1945, in the name of Harold A. Wheeler, and Serial No. 582,284, filed March 12, 1945, in the name of Michael J. Di Toro and assigned to the same assignee as the present invention.

Time-delay networks, as such, have long been known in the art and are in the form of a balanced or unbalanced circuit. A balanced delay network of the prior art comprises a pair of similar distributed windings coaxially wound about a common supporting core structure but with opposed pitches to contribute to the network uniformly distributed inductance and capacitance. The physical characteristics of the windings, such as dimensions, number of turns per unit length, and conductor size determine the total time delay of the network. The losses and imperfections of the windings determine the attenuation and the pass-band characteristics of the network. While such prior art time-delay networks have proved to be operative, they are subject to certain inherent limitations which may be undesirable in particular installations. For example, the arrangement is susceptible to two distinctly different modes of operation: (1) balanced or normal operation wherein the currents in corresponding portions of its windings are out of phase and (2) unbalanced or abnormal operation wherein the currents in corresponding portions of its windings are in phase. Additionally, a balanced circuit is generally required for transferring signal energy to or from the network.

An unbalanced delay network of the prior art comprises a single distributed winding and an associated ground-return path. The ground-return path is usually provided by a slotted metal tube which also serves as a supporting core structure for the winding. The capacitance between the winding and its core structure supplies the distributed capacitance of the network which, together with the inductance of the winding, determines the total time delay. A particular time delay may be obtained by appropriately selecting the physical characteristics of the winding and its core structure. Such an arrangement

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is subject to but a single mode of operation and an unbalanced circuit may be utilized for transferring energy with reference thereto. To this extent the unbalanced delay network is more desirable than the described balanced arrangement. However, such unbalanced networks of the prior art have been subject to serious loss problems. For example, the eddy-current loss in the core structure has been severe since the core is closely positioned with reference to a large portion of the surface of the winding in order to furnish the desired distributed capacitance in the network. Additionally, it is found that the core structure undesirably shields the magnetic field of the winding and reduces the inductance of the network.

It is an object of the invention, therefore, to provide an improved time-delay network for translating signal components included within a predetermined range of frequencies and which avoids one or more of the above-mentioned limitations of prior art arrangements.

It is another object of the invention to provide an improved time-delay network of the unbalanced or three-terminal type for translating with minimum attenuation signal components included within a predetermined range of frequencies.

It is a further object of the invention to provide an improved time-delay network for translating signal components included within a predetermined range of frequencies and having a relatively long time delay but reduced space requirements.

In accordance with the invention a time-delay network for translating signal components included within a predetermined range of frequencies comprises an elongated and substantially solid core structure of conductive material. The network includes an elongated winding insulated from but electrically coupled along its length to the core structure to provide in the network a distributed capacitance comprising the capacitance between the core structure and the winding for determining, in conjunction with the inductance of the winding, the time delay of the network. The core is constructed to have such conductivity that the eddy-current and conduction-current losses thereof are approximately equal at the mid-frequency of the aforesaid range of frequencies.

For a better understanding of the present invention, together with other and further objects thereof, reference is had to the following description, taken in connection with the accompanying drawing, and its scope will be pointed out in the appended claims.

In the drawing, Fig. 1 is a schematic representation of an unbalanced time-delay network in accordance with the present invention; Fig. 2 is a schematic circuit diagram utilized in discussing the attenuation properties of the network; Figs. 3 and 4 illustrate modifications of the delay network of Fig. 1; and Fig. 5 is a schematic circuit diagram utilized in discussing the attenuation properties of the Fig. 4 arrangement.

Referring now more particularly to Fig. 1, the time-delay network there represented is of the unbalanced or three-terminal type for translating signal components included within a predetermined range of frequencies. The network is in the form of a simulated transmission line and comprises an elongated and substantially solid core structure 10 of conductive material. Preferably, the material of the core structure also is such as to provide a high permeability for a purpose to be made clear hereinafter. Where the core structure is both conductive and magnetic, it may include comminuted graphite and iron particles molded into a conductive rod of any desired diameter and length.

The network also includes an elongated or distributed winding 11 wound around core structure 10 to be mechanically supported thereby. The winding is insulated from its supporting core structure by means of an insulating sleeve or tape 12, although this insulation may be omitted where the insulation of the winding has sufficiently high dielectric properties. Due to the inherent capacitance between winding 11 and conductive core 10, the winding is electrically coupled along its length to the core structure to provide in the delay network a distributed capacitance, namely, the capacitance between the core structure and the winding. This capacitance, in conjunction with the inductance of winding 11, determines the total time delay of the network since the total time delay of any such network is proportional to the geometric mean of its total inductance and total capacitance. The diameter, length and permeability of core structure 10, the size and type of conductor utilized in fabricating winding 11, the number and pitch of the winding convolutions are selected to afford such desired values of inductance and capacitance that the network produces a certain total time delay. In this connection, it will be appreciated that an increase in the diameter or length of the core structure and winding results in higher values of inductance and capacitance, while increasing the number of turns per unit length of the winding increases primarily only the inductance. Likewise, the inductance alone may be increased to a desired value by proportioning the core structure for higher permeability.

The time-delay network further includes a connector 13, having a substantially lower impedance than the core structure and connected thereto adjacent one end of winding 11, for providing a low-impedance path to a common terminal, usually ground, from the core structure. The common or ground terminal is designated 14 and the connection 13 thereto may comprise a silver-plated conductive strap. An input terminal 15 for applying signals to the network is provided at one end of winding 11, while an output terminal 16 for deriving delayed signals therefrom is provided at the opposite end of the winding.

The described arrangement will be seen to constitute an unbalanced or three-terminal network. It may be considered as a three-terminal network inasmuch as it comprises an input terminal 15, an output terminal 16 and a common or ground terminal 14. In the schematic circuit diagram of Fig. 2, which is approximately the electrical equivalent of the Fig. 1 arrangement, the distributed inductance of winding 11 is shown as series-connected inductors L_1, L_1 and the distributed capacitance between the winding and its core structure is designated by shunt-connected condensers C_1, C_1. This circuit arrangement including series-connected inductors and shunt-connected condensers essentially comprises a transmission line having a given total time delay. As will be made clear presently, the network is constructed through appropriate proportioning of the conductivity of its core structure to have a minimum attenuation over a given pass band for translating signal components included within a predetermined range of frequencies. By virtue of this feature, signal components included within a desired frequency range and applied to input terminal 15 are translated with minimum attenuation and distortion to output terminal 16.

In discussing the attenuation characteristics of the network of Figs. 1 and 2, the resistance of winding 11 will be neglected so that the attenuation to be minimized is determined largely by the eddy-current losses and the conduction-current losses of the core structure. The term "conduction-current losses" as herein used designates the losses resulting from current flow within the network as distinguished from losses attributable to induced currents, induced by actual curent flow within the network. The eddy-current losses which do result from induced currents are associated with the inductance of winding 11. These losses may be considered as occurring in the resistors R_e, R_e shown in shunt relation with the series-connected inductors L_1, L_1. The conduction-current losses on the other hand are associated with the currents flowing through these inductors and the return path to ground and may be considered to occur in the resistors R_c, R_c of Fig. 2. Since the magnitudes of both the eddy currents and the conduction currents are determined, at least in part, by the conductivity of core structure 10, the core conductivity is effective to determine the attenuation characteristic of the network and has a critical value for minimum attenuation. The optimum conductivity of the core, required for attaining minimum attenuation and maximum Q of the network, may be determined with the aid of the following expressions in which:

n=number of turns in winding 11.
a=radius of winding 11 (meters).
b=length of winding 11 (meters).
μ=permeability of core structure 10 (henries per meter).
L_1=inductance per unit length of winding 11 (henries per meter).
ρ=resistivity of core structure 10 (ohm × meters).
R_c=conduction-current loss resistance per unit length of network (ohms per meter).
R''=equivalent series resistance per unit length of network of eddy-current shunt loss resistance (ohms per meter).

R_s=effective series resistance per unit length of network of conduction-current and eddy-current loss resistances (ohms per meter).

$\omega=2\pi$ times the operating frequency.

$\omega_m=2\pi$ times the mid-frequency of the pass band of the network.

(′) indicates the preferred value of the factor to which it is affixed.

For the assumed conditions:

$$R_s=R_c+R'' \quad (1)$$

$$R_c=\frac{\rho}{\pi a^2} \quad (2)$$

$$R''=\frac{\pi\omega^2\mu^2a^4n^2}{8\rho b^2} \quad (3)$$

$$L_1=\frac{\mu n^2\pi a^2}{b^2} \quad (4)$$

$$R_s=\frac{\rho}{\pi a^2}+\frac{\pi\omega^2\mu^2a^4n^2}{8\rho b^2} \quad (5)$$

$$Q=\frac{\omega L_1}{R_s} \quad (6)$$

From Equations 1 and 5 it is seen that the attenuation caused by the conduction-current losses in R_c is independent of frequency while that attributable to the eddy-current losses in R'' varies directly as the square of the frequency. Also, it is to be noted that attenuation factors R_c and R'' vary in opposite senses with variations in the core resistivity ρ. Thus, the total attenuation R_s may be minimized by selecting a value of core resistivity which causes the factors R_c and R'' to be equal at the mid-frequency of the pass band of the network. Where this condition is established:

$$(\rho')^2=\frac{\pi^2a^6\omega_m^2\mu^2n^2}{8b^2} \quad (7)$$

$$\rho'=\frac{\pi a^3\omega_m\mu n}{2\sqrt{2}b} \quad (8)$$

$$R'_c=\frac{\rho'}{\pi a^2}=\frac{a\omega_m\mu n}{2\sqrt{2}b} \quad (9)$$

$$Q_{max}=\frac{\omega_mL_1}{2R'_c}=\sqrt{2}\,\frac{n\pi a}{b} \quad (10)$$

Equation 8 is an expression for the resistivity of core 10 resulting in minimum attenuation and optimum Q of the network. The expression includes only terms which are definitely known for a given network and permits the core resistivity to be computed readily. Equation 8 involves the permeability μ of the core structure which, as seen in Equation 4, also has a direct bearing upon the total inductance of winding 11. Having selected the permeability required for a desired inductance per turn or total inductance of winding 11 and having computed from Equation 8 the core resistivity for minimum attenuation, the percentage of conductive material to be included in the core structure may be readily determined for a core of a given length and given diameter. When the core is constructed in this manner its conductivity is such that the eddy-current losses and the conduction-current losses thereof are equal at the mid-frequency of the pass band of the network.

The Fig. 3 embodiment of the invention is generally similar to that of Fig. 1, corresponding components being identified by the same reference characters. In Fig. 3, however, core 10 has at least one and, preferably, a plurality of longitudinally or axially extending slots 20, 20. Such a core structure is obtainable by molding the core about radially disposed dielectric strips. The dielectric strips have a very small cross section as compared with that of the core 10 so that while the core includes longitudinal slots the slots are sufficiently small in cross section that the core may nevertheless be considered as substantially solid. The presence of the longitudinal slots modifies the eddy-current paths of the delay network by precluding a complete circumferential path around the periphery of the core. This arrangement still further reduces the total attenuation of the network and increases its Q in the manner described in the above-identified copending application Serial No. 582,285.

In Fig. 4 there is represented a further embodiment of the delay network of Fig. 1, the instant modification including a longitudinal non-magnetic conductor 30, conductively connected along its length to core structure 10 and connected by way of connector 13 to the common or ground terminal 14. More specifically, conductor 30 is embedded within the core so as to be conductively connected therewith and extends beyond each end of the core structure. Its projecting ends may be threaded, as illustrated, to facilitate securing the delay network to a supporting structure. Conductor 30 is selected to have a substantially lower impedance per unit length than that of core 10 and such a small cross-sectional configuration as compared with that of the core as to be linked by only a small fractional portion of the magnetic flux of winding 11. The conductor 30 may comprise a length of copper rod and has such a small radius in comparison with the radius of the core structure that the core may be considered as substantially homogeneous.

The schematic circuit diagram of Fig. 5 is the approximate electrical equivalent of the delay network of Fig. 4 and is generally similar to the schematic circuit diagram of Fig. 2, corresponding components thereof being designated by the same reference characters.

In determining the conductivity of core structure 10 of the Fig. 4 embodiment required to obtain minimum attenuation and maximum Q, it will again be assumed that the resistance of winding 11 is negligible. It will be further assumed that a single grounding conductive strap 30 is included in the core structure having an impedance per unit length which is also negligible. For the assumed conditions, conductor 30 of Fig. 5 may be construed as a ground plane associated with the network so that the conduction-current loss resistors R_c are inserted in the shunt arms of the network. In deriving the expressions for the construction of the network to obtain minimum attenuation and maximum Q, the following symbols in addition to those identified above are used:

a_0=radius of conductor 30 (meters).

C_1=distributed capacitance per unit length of the network (farads per meter).

R_k=characteristic impedance of delay network (ohms).

R_ρ=total radial resistance of core structure 10 (ohms).

ln=natural logarithm.

t_d=one-way delay of network (seconds).

t_{d1}=one-way delay of network per unit length (seconds).

θ_1=phase shift of network per turn of winding 11.

Where, as in the assumed embodiment of the core structure, a single conductive grounding strap 30 is provided:

$$R_s = R_c + R'' \tag{11}$$

$$R_c = \frac{\omega^2 C_1^2 R_k^2 \rho \ln\left(\frac{a}{a_0}\right)}{2\pi} \tag{12}$$

$$R'' = \frac{\pi \omega^2 \mu^2 a^4 n^2}{8 \rho b^2} \tag{13}$$

$$R_s = \frac{\omega^2 C_1^2 R_k^2 \rho \ln\left(\frac{a}{a_0}\right)}{2\pi} + \frac{\pi \omega^2 \mu^2 a^4 n^2}{8 \rho b^2} \tag{14}$$

From Equation 14 it is noted that in the network of Fig. 5 the attenuation per unit length caused by the conduction-current losses in R_c and the eddy-current losses in R'' both vary directly as the square of the frequency but vary in opposite senses with core resistivity ρ. The total attenuation per unit length caused by R_s may, therefore, be minimized by selecting the value of core resistivity which causes the attnuation factors R_c and R'' to be equal. Where the core structure is so selected:

$$(\rho')^2 = \frac{\pi^2 \mu^2 a^4 n^2}{4 C_1^2 R_k^2 b^2 \ln\left(\frac{a}{a_0}\right)} \tag{15}$$

$$\rho' = \frac{\pi \mu a^2 n}{2 C_1 R_k b \sqrt{\ln\left(\frac{a}{a_0}\right)}} \tag{16}$$

$$R'_s = \frac{\rho' \omega^2 C_1^2 R_k^2 \ln\left(\frac{a}{a_0}\right)}{2\pi} = \frac{\omega^2 C_1 R_k \mu a^2 n}{4b} \sqrt{\ln\left(\frac{a}{a_0}\right)} \tag{17}$$

$$Q_{max} = \frac{\omega L_1}{2R'_s} = \frac{2\pi n}{b \omega t_{d1} \sqrt{\ln\left(\frac{a}{a_0}\right)}} =$$

$$\frac{2\pi n}{\omega t_s \sqrt{\ln\left(\frac{a}{a_0}\right)}} = \frac{2\pi}{\theta_1 \sqrt{\ln\left(\frac{a}{a_0}\right)}} \tag{18}$$

$$R'\rho = \frac{\rho \ln\left(\frac{a}{a_0}\right)}{2\pi b} = \frac{R_k}{4\pi n} \sqrt{\ln\left(\frac{a}{a_0}\right)} \tag{19}$$

Equation 16 is an expression for the resistivity of core structure 10 of the network, resulting in minimum attenuation and maximum Q of the network. The factors of this equation are definitely known for a given network construction so that the particular core construction necessary for minimum attenuation for arrangements of the type illustrated in Fig. 4 may be readily determined. In this construction, as shown by Equation 16, the core resistivity is independent of frequency. Hence, the optimum core resistivity causes the eddy-current losses in the core structure to be equal to the conduction-current losses thereof at all frequencies within the pass band of the network.

As described above, conductor 30 has a very small cross section as compared with that of core structure 10. For this reason the conductor occupies but a small fractional portion of the magnetic field established by winding 11 and therefore is linked by only a small fractional portion of the magnetic flux of the winding. While a single conductor is illustrated in the core structure of the Fig. 4 embodiment, a plurality of similar low-impedance conductors may be provided if desired. The advantage of increasing the number of such conductors is pointed out in related copending application Serial No. 582,284.

While both experience and theory show that best results are obtained when the eddy-current and conduction-current losses of the time-delay networks are equal at the mid-frequency of the pass band, the advantages of the invention may nevertheless be obtained to a substantial degree if these losses are approximately equal. The term "approximately equal" as used in the description and appended claims is intended to mean that one of the losses may be between 1.0 and 0.1 the other. Where the attenuation factors are proportioned within the limits of this definition, the ratio of the actual Q of the network to the maximum Q, obtained when the eddy-current and conduction-current losses are equal, is greater than 0.57.

Terminals 14, 15 and 16 permit the delay network to be coupled as desired in signal-translating systems. Such a network is subject to a wide variety of applications and may be utilized, for example, to obtain a desired time delay of applied transient signals. Also through appropriate termination of the output circuit of the network, echoes or reflections of applied signals may be obtained, as with well-known reflecting transmission-line arrangements. Additionally, such a network is useful in pulse-generating systems wherein similar time-delay networks determine the duration and spacing of the generated pulses.

Each of the described arrangements has the advantages of an unbalanced or three-terminal network and minimum attenuation to applied signals within a desired range of frequencies. Furthermore, as pointed out above, by appropriate selection of the permeability of core structure 10, the delay network may exhibit a very high inductance and, consequently, produce unusually long time delays for a network structure of given physical dimensions.

While there have been described what are at present considered to be the preferred embodiments of this invention, it will be obvious to those skilled in the art that various changes and modifications may be made therein without departing from the invention, and it is, therefore, aimed in the appended claims to cover all such changes and modifications as fall within the true spirit and scope of the invention.

What is claimed is:

1. A time-delay network for translating signal components included within a predetermined range of frequencies comprising, an elongated and substantially solid core structure of conductive material, an elongated winding insulated from but electrically coupled along its length to said core structure to provide in said network a distributed capacitance comprising the capacitance between said winding and said core structure for determining in conjunction with the inductance of said winding the time delay of said network, said core structure having such conductivity that the eddy-current and conduction-current losses thereof are approximately equal at the mid-frequency of said range.

2. A time-delay network for translating signal components included within a predetermined range of frequencies comprising, an elongated and substantially solid core structure of conductive and magnetic material, an elongated wind-

ing insulated from but electrically coupled along its length to said core structure to provide in said network a distributed capacitance comprising the capacitance between said winding and said core structure for determining in conjunction with the inductance of said winding the time delay of said network, said core structure having such conductivity that the eddy-current and conduction-current losses thereof are approximately equal at the mid-frequency of said range and having such permeability that said winding has a predetermined inductance per turn.

3. A time-delay network for translating signal components included within a predetermined range of frequencies comprising, an elongated and substantially solid core structure of conductive material having at least one longitudinally extending slot, an elongated winding insulated from but electrically coupled along its length to said core structure to provide in said network a distributed capacitance comprising the capacitance between said winding and said core structure for determining in conjunction with the inductance of said winding the time delay of said network, said core structure having such conductivity that the eddy-current and conduction-current losses thereof are approximately equal at the mid-frequency of said range.

4. A time-delay network for translating signal components included within a predetermined range of frequencies comprising, an elongated and substantially solid core structure of conductive material, an elongated winding insulated from but electrically coupled along its length to said core structure to provide in said network a distributed capacitance comprising the capacitance between said winding and said core structure for determining in conjunction with the inductance of said winding the time delay of said network, and a longitudinal conductor conductively connected along its length to said core structure and having a substantially lower impedance per unit length than said core structure and such cross-sectional configuration as to be linked by only a small fractional portion of the magnetic flux of said winding, said core structure having such conductivity that the eddy-current and conduction-current losses thereof are approximately equal at all frequencies within said range.

5. A time-delay network for translating signal components included within a predetermined range of frequencies comprising, an elongated and substantially solid core structure of conductive material, an elongated winding insulated from but electrically coupled along its length to said core structure to provide in said network a distributed capacitance comprising the capacitance between said winding and said core structure for determining in conjunction with the inductance of said winding the time delay of said network, and a longitudinal conductor embedded in said core structure so as to be conductively connected thereto along its length and having a substantially lower impedance per unit length than said core structure and such cross-sectional configuration as to be linked by only a small fractional portion of the magnetic flux of said winding, said core structure having such conductivity that the eddy-current and conduction-current losses thereof are approximately equal at all frequencies within said range.

6. A time-delay network for translating signal components included within a predetermined range of frequencies comprising, an elongated and substantially solid core structure of conductive material, an elongated winding insulated from but electrically coupled along its length to said core structure to provide in said network a distributed capacitance comprising the capacitance between said winding and said core structure for determining in conjunction with the inductance of said winding the time delay of said network, and a longitudinal conductor disposed within said core structure so as to be conductively connected thereto along its length and extending beyond the ends of said core structure, said conductor having a substantially lower impedance per unit length than said core structure and such cross-sectional configuration as to be linked by only a small fractional portion of the magnetic flux of said winding, and said core structure having such conductivity that the eddy-current and conduction-current losses thereof are approximately equal at all frequencies within said range.

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