Dec. 11, 1945. G. L. TAWNEY 2,390,563

ELECTRICAL TIME DELAY LINE

Filed Oct. 14, 1941

FIG. 1

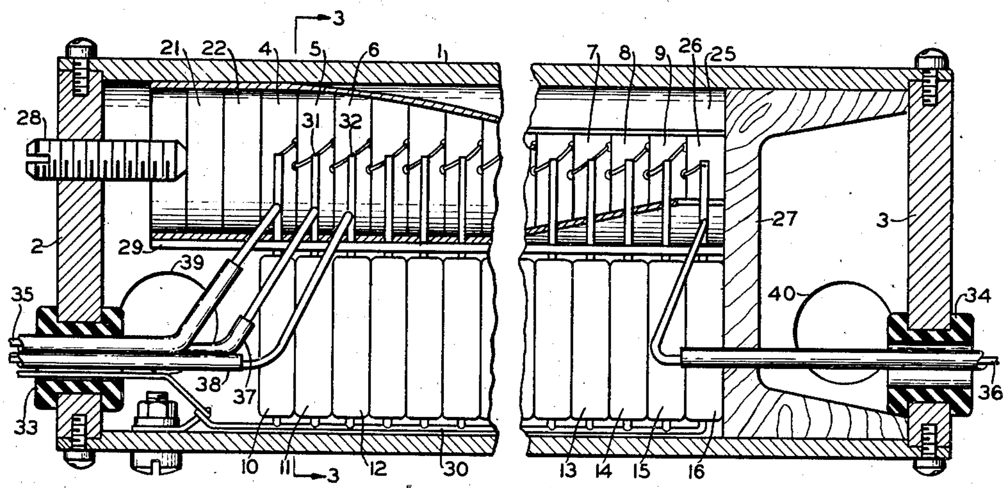


FIG. 2

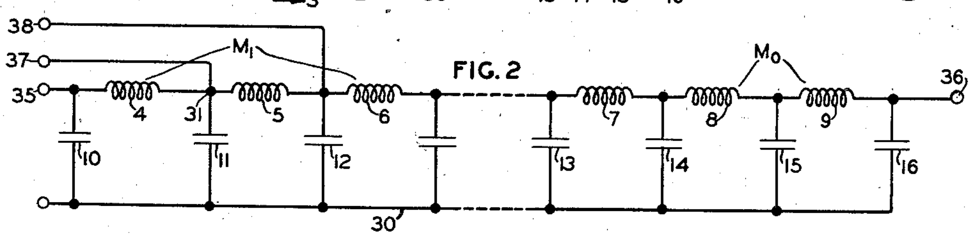


FIG. 4

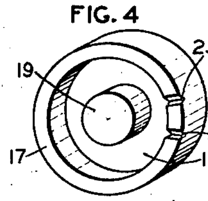


FIG. 5

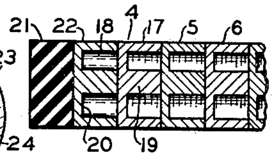


FIG. 3

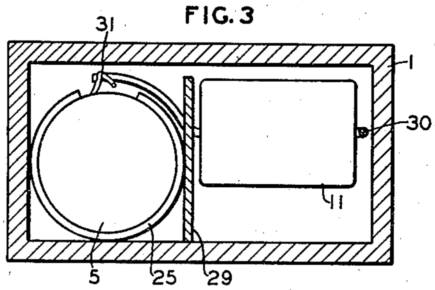


FIG. 6

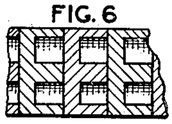
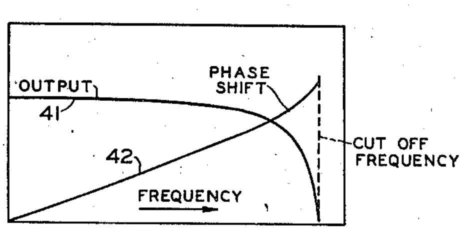


FIG. 7



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2,390,563

ELECTRICAL TIME DELAY LINE

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Application October 14, 1941, Serial No. 414,928

2 Claims. (Cl. 178—44)

This invention relates, generally, to the use of multi-section uniform filter networks as time delay lines, and, more specifically, to a novel type of delay line designed to give linear and calculable phase shift as a function of frequency and nearly constant amplitude of output with frequency.

It is well known in network theory and practice that a constant K type of low pass multi-section uniform filter made up of T sections produces a phase characteristic which is approximately linear with frequency on the low frequency side of the band passed by the filter. This quantity K for such a filter is a constant at all frequencies, and is defined as the square root of the product of the series and shunt impedances of the basic T section of the filter. Such filters usually have all sections identical with the exception of the end sections. The latter may be half sections suitable for connecting the filter to terminating impedances. It is also common knowledge that an optimum amount of mutual inductance between the consecutive inductances of a series inductance T section filter of many uniform sections will make the phase-frequency function a linear one over a considerably longer part of the pass band. This is indicated in the article "Extensions to the theory and design of electric wave filters" by O. J. Zobel, Bell System Technical Journal, April 1931, pp. 284–341 (Monograph B-556).

For instance, let us define a new constant k_0 by the formula:

$$k_o=\frac{2M_o}{L}$$

where M_0 is the mutual inductance between adjacent series inductances L of the network. The constant k_0 may be referred to as the coupling coefficient for the section. It has been found empirically that the phase characteristic can be made more linear if k_0 is made to lie in the range $.25<k_0<.45$ and much more so for the lesser range $.35<k_0<.40$, when suitable mutual inductance between alternate coils is provided as discussed below.

Such multi-section filters are suitable for use as delay networks for steady state frequencies or for transients, so long as the frequency components of such input signals lie on the linear portion of the phase characteristic, i. e. somewhat below the cut-off frequency. In delay networks, it is also necessary that this cut-off frequency be sufficiently high to pass all or most of the components of the input signal with little relative attenuation. If these two requisites are satisfied, the output signal is free from phase and amplitude distortion, and an input transient signal will emerge from the network unchanged in form, though reduced in amplitude.

One of the main difficulties in the practical realization of such a design lies in the physical positioning of the series inductive elements of the filter so that interaction between them will be proper, i. e., so that k_0 will have a useful value. Another difficulty lies in the necessity for maintaining high Q inductive elements so that the network gives small attenuation. The value of Q (which is defined for a coil in the art by the formula:

$$Q=\frac{\omega L}{R_L}$$

where ω is the frequency, L the inductance of the coil, and R_L its alternating current resistance) is frequency dependent for most types of coils, and so the coil design should make R_L approximately a direct function of frequency. Shielding from external effects is, of course, necessary at all frequencies at which such delay networks are most useful.

I have found that the coupling k_1, between any pair of alternate coils of the network (k_1 being defined by

$$k_1=\frac{2M1}{L}$$

serves as a second order correction to the phase characteristic. The optimum value of k_1 for values of k_0 such that $.35<k_0<.40$ is found to be of the order of .02 to .06.

It is then the object of this invention to provide a uniform multi-section T element delay network of novel design and construction which has a linear phase characteristic up to very high radio frequencies and over a large portion of the pass band.

Another object of this invention is the provision of such a delay network having minimum relative attenuation of all frequency components over a very large range.

Another object of the invention is to provide a novel design for such a delay network, said design being compact in form, adaptable to easy manufacture and modification, and said design being readily shielded from external electromagnetic, electrostatic, thermal, vibratory and other disturbances.

Still another object of this invention is to provide such a delay network having properties making it possible to use portions of the delay time available in the network and allowing the network to be used in cascade with other similar networks to provide a greater delay time than is obtainable in one unit of such a delay network.

Yet another object of this invention is the provision of an inductance whose Q is approximately frequency-independent and one adapted for use in groups in delay or other networks, wherein the mutual inductance between adjacent coils and between alternate coils is chosen to still further improve the phase frequency characteristics of the delay line.

Other objects and advantages will become apparent from the specification, taken in connection with the accompanying drawing wherein one embodiment of the invention is illustrated.

In the drawing,

Fig. 1 is a partial cross section of the delay network, showing the compact distribution of its component elements.

Fig. 2 is an equivalent circuit of Fig. 1.

Fig. 3 is a cross section view taken along the line 3—3 of Fig. 1 and turned 90 degrees.

Fig. 4 is a perspective view of one of the coil cores as used in Fig. 1.

Fig. 5 shows a cross section of a series of these inductances as used in a network.

Fig. 6 is a modification of Fig. 5.

Fig. 7 is a graph useful in explaining the characteristics of the delay network.

Other objects and advantages of this invention will become apparent as the description proceeds.

The physical arrangement of the filter network of my invention is shown in Fig. 1, Fig. 2 being an equivalent circuit for the network of Fig. 1. The network is mounted inside of case **1** of suitable length which, as shown in Fig. 3, may be of rectangular cross-section. The network is made up of a series of T elements, as typified by inductances **8** and **9** and capacitance **15** of Figs. 1 and 2.

The novel design of the inductances **4**, **5**, **6**, . . . **7**, **8**, **9** being one of the chief features of my invention, I first shall describe these inductances. To obtain a constant Q inductance having self-shielding properties I use a core of powdered ferromagnetic material of a type in which the core surrounds the coil. The finely powdered magnetic material of the core is bonded by a Bakelite or other matrix material and is molded and pressed from dies in a manner well known to manufacturers producing radio transformers for use in intermediate frequency ranges. The material may be, for example, about 90% by weight iron, although I may choose other percentages by altering the geometry of the material of the coil, or by altering the design of the coil used in the core. The core is shaped as shown in Fig. 4 in perspective and in Fig. 5 in cross section. An annular groove **18** formed by the die in the material provides a recess for the coil, the outer wall **17** providing proper shielding from external disturbances and slight coupling to non-adjacent inductances, the reentrant portion **19** providing a centralizing holder and magnetic circuit closer for the coil, and the back wall **20** providing a proper value of the coupling k_0 to the adjacent inductance in the series. The coils themselves are made up of a suitable number of turns of, preferably, honeycomb-wound Litz or solid wire, depending on the desired cut-off frequency. The coil is then slipped into the annular groove **18**, its lead wires being brought outside the core through notches **23** and **24**. For a network of given time delay, the required number of these inductances is placed as shown in Fig. 1 axially in an open tubular paper holder **25**, their lead wires being oriented vertically through the open slot in the top of the tube. At the ends of the series are placed cores **22** and **26**, these cores containing no coils, as is shown in Fig. 5. The series of inductances is placed in the case **1**, butting against spacer **27**, and the screw **28** is adjusted against plate **21** which may be of Bakelite or other material until the coils are firmly held in place.

Condensers **10**, **11**, **12**, . . . **13**, **14**, **15** may be of any compact low loss type, such as the silver-mica rectangular molded condensers well known to the radio art. Their sides being ground flat, one lead of each condenser is soldered to ground wire **30**, the other lead of each condenser being projected through the suitable holes in insulating holder **29**, as seen in Fig. 3, and soldered to the coil lead wires, as shown at **31** and **32** in Fig. 1. Terminal condensers **10** and **16** are made half the value of the condensers **11**, **12**, . . . **13**, **14**, **15**, so that delay lines of equal characteristic impedance may be cascaded together without the use of any external matching sections.

Grommets **33** and **34** are provided in end plates **2** and **3** for shielded terminal wires **35** and **36**, respectively. Adjustability in time delay may be had by providing leads which tap the network at any desired time delay, such as shielded leads **37** and **38**, which illustrate the manner in which the time delay may be decreased by either once or twice the delay introduced by each T-section. These taps may be placed at any point in the line, however.

Holes **39** and **40**, normally plugged when only one unit of the network is used, may be used for the lead wires when it is desirable to stack such units one on top of the other to obtain multiples of the delay time obtainable from a single unit.

As illustrated in Fig. 1, the use of either of these taps **37**, **38** would require that a very high load impedance be used with the tap selected, and that the unused end of the line have placed across it a terminating impedance (across leads **30** and **35**). It is obvious that such impedances, together with any necessary switching arrangements, might also be placed in the delay line case. Fractional delay times may be also easily provided by inserting Bakelite or other spacers in place of a number of T-sections removed.

All of the remaining empty space inside the filter case may be filled with any of the well known types of wax or pitch used for such purposes in radio manufacture, thus safe-guarding the network from the destructive effects of humidity, vibration, et cetera.

To adjust the phase and amplitude characteristics of the inductances, as shown by graphs **42** and **41**, respectively, of Fig. 7, so that the phase is linear and the output flat over as large a frequency range as possible, the values of k_0 and k_1 may usually be varied by altering the dimensions of the wall **17** or base **20**, or by many other changes in dimension, separately, or in combination, or by changing the properties of the core material or of the coil. It has been found that the adjustments in k_0 and k_1 which give a linear phase characteristic make it possible to accurately compute all of the constants of the delay line, including its characteristic impedance Z_k and its delay time T, as defined by the formulae:

$$Z_k=\sqrt{\frac{L}{C}(1+k_0)}$$

$$T=\sqrt{LC(1+k_0)}$$

Delay lines of this construction have been studied, of which the following data is shown as an example. A delay line of 180 T-sections, made up of condensers of 100 micro-micro-farads capacity and coils of 3.6 millihenries has a delay time of 120 microseconds with attenuation of about 12 decibels and a characteristic impedance of 7000 ohms over a range whose upper limit is very near a cut-off frequency of 550 kilocycles. Thus, a signal with no frequency components above 500 kilocycles will pass through the network unchanged in shape, reduced in power by 12 decibels, and delayed 120 microseconds in time. It has been found that this type of delay line has useful properties up to a cut-off frequency of 25 megacycles.

As many changes could be made in the above construction and many apparently widely different embodiments of this invention could be made without departing from the scope thereof, it is intended that all matter contained in the above description or shown in the accompanying drawing shall be interpreted as illustrative and not in a limiting sense.

Having described my invention, what I claim and desire to secure by Letters Patent is:

1. An electrical delay line embodying a substantially uniform network comprising a plurality of series-connected inductances each comprising an open-ended shielding core and a coil positioned therein, means for holding said cores in a row, whereby the open end of one core is closed by the closed end of the succeeding core, the wall thicknesses of said cores being chosen to provide a coupling coefficient between adjacent coils of a value between .35 and .40, and a coupling coefficient between alternate coils of the order of .02 to .06, and a plurality of capacitative shunt elements substantially uniformly distributed along said line.

2. An electrical delay line embodying a substantially uniform network comprising a plurality of series-connected inductors each comprising an open-ended shielding core having a tubular outer wall, a disc end section, a reentrant portion, and a coil positioned on said reentrant portion within said tubular outer wall; means for holding said cores in a row in uniform alignment with said reentrant portions extending from the respective disc end sections in a predetermined direction along a common axis of said series-connected inductors; the dimensions of said disc end sections being so chosen in relation to the dimensions of said reentrant portions and said outer tubular walls as to provide a desired coupling coefficient between .25 and .40 between adjacent inductors, and a desired coupling coefficient between .02 and .06 between alternate inductors; and a capacitor connected between a common conductor and each electrical circuit junction of adjacent inductors, whereby substantially uniform effective time delay is provided in said delay line over an extremely wide frequency range.

GERELD L. TAWNEY.