April 15, 1969 G. A. SENF 3,439,293

DELAY LINE

Filed Aug. 4, 1965 Sheet 1 of 2

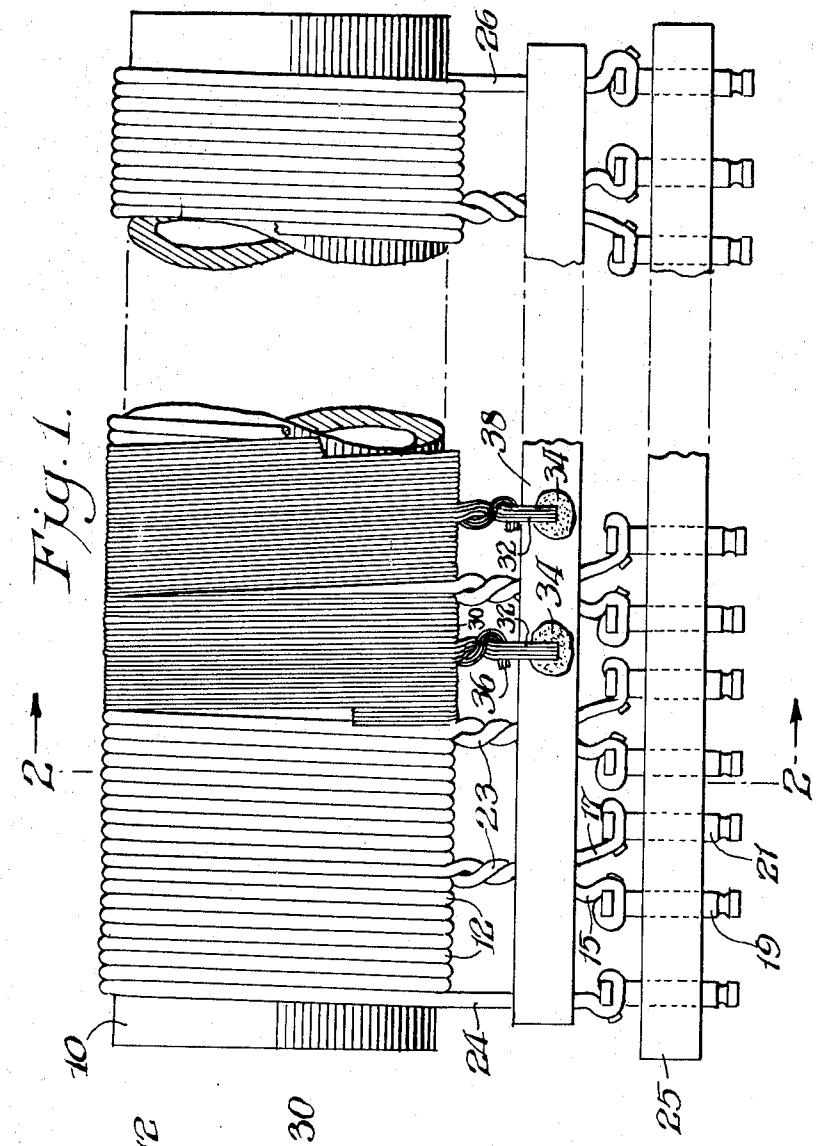


Fig. 1.

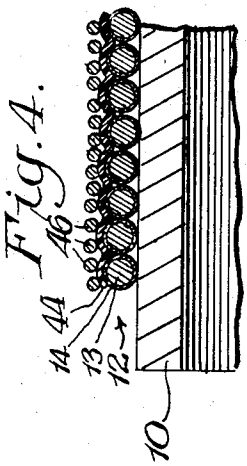


Fig. 4.

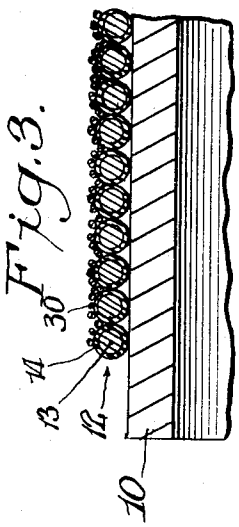


Fig. 3.

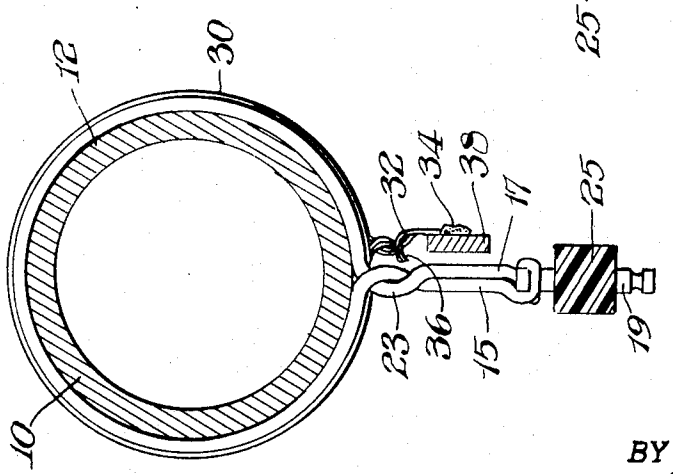


Fig. 2.

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Fig. 5.

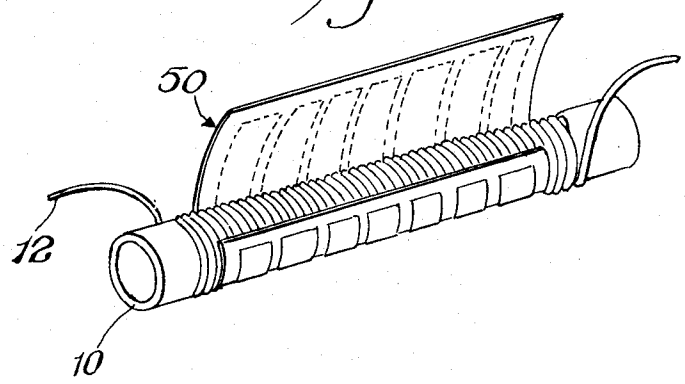
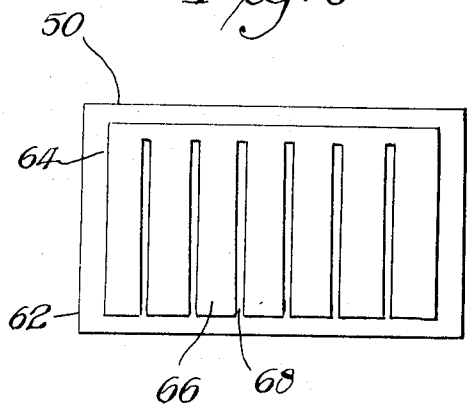


Fig. 6



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DELAY LINE

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U.S. Cl. 333—29 10 Claims

ABSTRACT OF THE DISCLOSURE

A delay line with minimum phase distortion at high frequencies is provided by winding a plurality of conductive ground sections over a principal winding and in an opposite direction to that of the principal winding. Each ground section has one end electrically connected to a common ground plane conductor with the other end left unconnected.

The present invention relates to delay lines, particularly those of the distributed type.

Delay networks having distributed parameters are often provided in the prior art by a structure having a coil or winding electrically coupled along its length to a longitudinally slotted core. Input and output connections are made to the coil and the core grounded to establish a network having a distributed series inductance and distributed shunt capacitance.

Phase distortion, due to the mutual or self induction of the coil which limits the network to low frequencies, is reduced in this type of line by a number of means, such as by the use of large coil diameters, the use of shorted turns adjacent to the coil or by capacitively shunting portions of the coil with longitudinal conductive patches.

These arrangements, while satisfactory for some uses, are generally difficult to manufacture and are still limited to relatively low frequencies for reasonable pulse fidelity.

Among the objects of the present invention is the provision of novel delay lines that are compact, efficient, simple to manufacture and not very susceptible to external influences.

A further object of the present invention is the provision of novel delay lines having minimum phase distortion.

A still further object of this invention is to provide a delay line of simplified structure in which distributed shunt capacitance and phase control are provided by a plurality of ground windings electrically coupled to a series inductance coil.

The foregoing as well as additional objects of the present invention will be more fully appreciated from the following description of several of its exemplifications, reference being made to the accompanying drawings wherein:

FIGURE 1 is a front view of a delay line typical of the present invention, parts being broken away in the interest of clarity;

FIGURE 2 is a sectional view taken along the line 2—2 of the delay line of FIGURE 1;

FIGURE 3 is a fragmentary sectional view giving some further details as to the arrangement of the windings in the delay line of FIGURES 1 and 2; and

FIGURE 4 is a view similar to FIGURE 3 showing a modified construction of the delay line pursuant to the present invention.

FIGURE 5 is a perspective view of a further embodiment of this invention.

FIGURE 6 is a view of the novel ground winding utilized in the embodiment of FIGURE 5.

In general, the objects are attained in accordance with this invention by providing a plurality of ground winding sections inductively and capacitively coupled to a principal winding and having one end connected to a common ground conductor and the other end unconnected.

In particular, the objects are attained in accordance with this invention by providing a principal winding layer of turns of electrical conductor and a plurality of ground winding sections wound respectively in close inductive and capacitive linkage with successive portions of the principal winding, each ground winding section being a single conductor or a multi-filar bundle of conductors, the ground windings being each wound in the direction opposite to the direction in which the principal winding is wound, each ground winding section having a corresponding end electrically connected to a common ground plane conductor, and having the opposing end unconnected.

The individual turns of the windings can be insulated from each other by winding each from insulated wire such as standard magnet wire. Such insulation can also serve to insulate the ground sections from each other as well as from the principal windings. A dielectric sheet, which also helps insulate the windings, may be utilized to space the ground winding and control the capacitance. This can be placed around the principal windings as by helically wrapping a plastic tape around them during their winding or after their completion.

In the interest of flexibility the principal winding can have one or more taps with external connections so that the signals to be delayed can be passed through selectable portions of the principal winding to obtain delays corresponding to any part of the maximum delay obtainable when using the entire principal winding to carry the signals. Where no taps are used a layer of insulation is more readily applied as a band having a width equal to or somewhat greater than the length of the principal winding. A single wrap of such band will do a good job of spacing the ground plane windings further from the principal winding even when the band has a thickness of as little as ¼ to 5 mils. Similarly, where no principal winding taps are used the ground windings and spacing dielectric may be more readily applied as a castellated metallized film.

The series inductance and the shunting capacitance per unit length as well as the phase compensation, although interdependant to some degree, may be individually controlled to satisfy a wide variety of specifications. Thus, the series inductance per unit length may be increased by reducing the wire size to allow more turns per unit length or by adding high permeability elements to the assembly, as for example in the form around which the windings are wound.

The capacitance per unit length and the phase compensation may be increased by reducing the wire size of the ground coils. In this way, the spacing between the windings may be reduced and the capacitance correspondingly increased. It should be noted, however, that the thickness of wire insulation, or tape insulation if used, will also determine the radial separation of the windings and thus the capacitance.

Phase compensation is increased by the reduced wire size of the ground windings since the number of turns per length and the corresponding inductance of the ground windings is increased. The length of the ground sections will also determine the phase compensation since such influences the effective mutual inductance of the principal winding. In this regard a ground section length of 1 to 3 times the coil diameter is effective and an optimum length of 1.5 times is generally preferred.

The delay lines of the present invention are easily made with figures of merit between 10 and 15, for short nano-

second delays. This figure of merit is the ratio of the delay time to the minimum line rise time.

Turning now to the drawings, the delay line of FIGURES 1, 2 and 3 is built on a form **10** which is generally cylindrical in shape, having a circular, elliptical or semi-elliptical cross section in which sharp corners are avoided, and is an electrically non-conductive member of ceramic or of resin like polystyrene or a cross-linked ethylene glycol polyester of maleic acid or the like.

A principal winding **12** of insulated copper wire such as ordinary magnet wire is wound on the form as a single layer with the turns of each layer touching each other. During the winding a number of taps can be brought out as loops, for example. Each loop can be connected to a terminal or, as in the embodiment of FIGURE 1, the loops can be cut to provide separate cut ends **15** and **17** which can be connected to separate terminals **19** and **21**. The taps can be equally spaced along the winding, or if preferred the spacing can be varied to make a more flexible selection of delay. The turns of the principal winding can be mechanically held in place by twisting the loop type taps, as indicated at **23**, or by a suitable clamping fixture until the ground windings have been applied and the unit impregnated. The beginning **24** and end **26** of the principal winding **12** are also connected to terminal pins and as in the illustrated embodiment these pins along with tap terminals **19** and **21** may be molded in place in a plastic terminal board **25**.

The principal or series inductance winding may also utilize one or more uncoated wires with each turn insulated from the next by an insulated wire or an insulating spacer wound between them. The principal winding can, if desired, have its turns spaced from each other by having the winding core helically grooved and arranging for the turns to lie in the groove.

Wrapped around the principal winding **12** are a number of sections of a ground plane winding, one section of which is shown at **30**. Section **30** is made, for example, of a bundle of five insulated wires wound in multi-filar fashion in the direction opposite to that in which the principal winding is wound. The ground plane sections are in the form of a single layer in which the turns of the layer have five strands each. While FIGURE 1 shows the strands wrapped fairly uniformly so that no strand crosses any other strand, the ground plane windings can also be wound in random fashion so that there will be quite a few strands crossings.

One end of each ground plane sections **30** extends from the winding, as shown at **32**, and is connected as by a solder joint **34** to a ground plane conductor **38** shown as a strip of metal. The other end of section **30** is left unconnected as indicated at **36**. The unconnected end **36** must not be allowed to contact other portions of the line, thus in some embodiments the end **36** is not twisted around the ground connection **32** but bent back so that the cut end will not be shorted to any portion of the structure.

This use of ground windings having one end unconnected provides a distinct advantage over the prior art in that capacitive shunting to ground and phase compensation are provided in the single section, and further, such phase compensation does not introduce eddy current losses as in the shorted turn devices of the prior art.

One convenient way for arranging the ends **32** and **36** in the above manner is to wind the ground winding conductor or multi-filar conductors as a single integral winding from one end of the principal winding to the other, pulling out loops at the turns where the section ends are to be located. The coils are then secured by impregnating the structure with varnish, epoxy or other suitable coating or by tape or the like. The loops are then cut and the ends suitably arranged, as indicated. It is generally preferred to have the ground plane sections extend from near the beginning to near the end of the principal winding and for these sections to each have the same number of turns, however, sections of varied length or varied number of turns may be employed, of course, where a variation in phase compensation is desired throughout the length of time.

In FIGURE 1 portions of the ground plane winding have been broken away to better show the principal winding underneath it. The wire diameter of either winding whether single conductor or multi-filar etc. may be utilized to vary the parameters of the line, as described earlier. Furthermore, for maximum negative mutual inductance the ground windings should oppose the principal winding.

As pointed out above, the ordinary enamel used to insulate copper magnet wire provides adequate insulation and in the interest of simplicity the turns of each winding can be closely wound, that is with the successive turns in uniform engagement with each other around their entire periphery.

The entire assembly as illustrated in FIGURES 1 and 2 can be potted or sealed in a container with the terminal pins and ground plane conductor available for external connections to the circuits supplying and receiving the signals to be delayed. For greater compactness the ground plane conductor **38** can be carefully folded against the windings and entirely embedded in a potted assembly, for example, with only a lead extending from that conductor to one of the terminal pins. The terminal board, where used, can also be carefully folded back against the windings. In either case, care must be exercised so as to avoid any shorting of the folded back members to other parts of the structure.

The windings will generally be disposed as coaxial layers having the ground winding more or less covering the principal winding, as is illustrated in FIGURE 3. Because of this disposition the ground plane windings have an electrostatic shielding effect on the principal winding and greatly reduce the sensitivity of the assembly to nearby conductors or the like. Accordingly the delay lines of the present invention can be physically located in fairly close juxtaposition to other circuit elements.

It should be obvious, however, that other configurations may be useful. For example, the principal winding may be applied over the ground winding sections. Increased capacitance and additional phase compensation may be realized by having appropriately connected ground winding sections internal and external to the principal winding. In fact, several layers of alternate windings may be utilized in this manner.

The principal winding **12** is shown in FIGURE 3 as a single strand **13** of copper or the like having an insulated coating **14**. Ground winding **30** is illustrated as multi-filar wire. Either winding may of course be single or multi-filar. Although the individual turns must be insulated from each other, as indicated earlier, individual strands of multi-filar windings may be separately insulated, or not, as desired.

Because the ground plane windings in the construction of FIGURES 1–3 are made with a relatively thin conductor, the ground plane turns will at least partially find their way into the hollows formed adjacent the junction of successive turns in the principal winding. This establishes a relatively high capacitance between the principal winding and the ground plane and is particularly advantageous for low impedance lines. For some purposes, as for example where maximum capacitance is not essential, the ground plane windings can be spaced from the principal winding. This is illustrated in FIGURE 4 where the principal winding **12** is of the same type as shown in FIGURES 1–3 and a layer **44** of high or low dielectric constant insulator is wraped around the entire principal winding before the ground plane sections are built up. In tthe construction of FIGURE 4 the ground plane windings **46** are shown as bi-filar, but the number of strands that can be used can be as many as ten or more.

The principal winding can be made bi-filar, particularly if its DC resistance is to be minimized. Either in-

sulated or uninsulated wire can be used for the bi-filar conductors of the principal winding if adjacent turns are insulated, and taps can be pulled out from the bi-filar winding as easily as for a mono-filar principal winding. The wires used in any or all of the windings can also be made of conductors other than copper such as aluminum or silver, or they can even be hollow. Silver-plated solid copper wire is also a very effective winding material.

Instead of having the wires of circular cross-section as indicated in the drawings, they can have any other cross-section including square, rectangular or oval, by way of examples. Square or rectangular wire, when wound in untwisted form, can in some cases be packed closer together than round wires, however, the capacitance from such principal winding to the ground plane conductors may be materially reduced since the radial separation of the coaxial windings will be somewhat greater than that possible with the arrangement shown in FIGURE 3, for example. In low impedance lines, the conductor used for the ground plane windings is generally of such small size that wires of any type of cross-section will provide about the same type of operation.

Although, it might be assumed that the current-carrying ability of the turns of the ground windings should be approximately equal to that of the principal winding conductor it has been found current carrying ability can be much less in the ground windings due to the shorter path length of high frequencies in this winding. In any event, the current carrying ability of the device is not measured by the total cross-sectional area of the conductors since the currents generally carried are of relatively high frequencies and therefore concentrate near the outer skin of the conductors.

Consequently, thin metallic strips may be utilized for the ground windings as illustrated in FIGURES 5 and 6 wherein a core **10** and principal winding **12** are shown having a castellated metallized film **50** as the ground windings.

The film **50** which comprises a dielectric base layer **62** of polytetraethelene or the like and a metallic film **64** of high conductivity metal such as copper or the like is convolutely wound over the principal winding **10** preferably in a direction opposite to that of the principal winding.

The film is illustrated for clarity in the partially unwound condition, however, it should be understood that one or more turns of the metallic film is anticipated. As shown, the plastic base **62** not only carries the metallic film **64** but additionally insulates and spaces the film from the principal winding **10** and from its own overlapping turns. A separate dielectric film could of course also provide such insulating and spacing.

Individual ground sections are provided by the castellated design illustrated in FIGURE 6 wherein narrow slots **68** transverse from one border of the metal film **64** to near the opposing border to form castellations **66**. Other suitable designs are also possible.

The entire delay line of the described invention provides as much as 50 nanoseconds of delay in a physical bulk about ¼ inch by ¼ inch by 1 inch. A solid or hollow coil form which is round or oval or any other cross-section as long as sharp corners are avoided, is suitable for holding the windings and if desired the coil form can be made retractable and removed after the windings are all completed and secured against each other. The use of a coil form is particularly desirable when high permeability elements are to be incorporated in the delay line for the purpose of increasing the inductance. Powdered iron or other magnetic materials can then be incorporated in the coil form or applied as a coating over it or even inside of it.

It should be noted that winding the ground plane sections in the same direction as that of the principal winding provides less negative mutual inductance and gives delay lines with lower figures of merit; however, this may be utilized at least where asymmetrical distortion is desired.

The length of the delay line can be increased if delays of relatively large magnitude are desired, or shorter lines can be connected together in series for the same purpose. A plurality of such lines can be potted as an integral series-connected assembly with the various taps suitably identified to indicate the delays that are obtainable. Because of the efficiency of the construction of the present invention it is generally not necessary to have a delay line wound around a form that is larger than ½ inch in diameter, or with an axial length of winding greater than about 6 inches. The number of turns in each ground plane winding section is selectable in accordance with the amount of mutual inductance or phase compensation desired.

The following examples show two different delay lines constructed in accordance with the present invention, as well as their electrical characteristics:

EXAMPLE I

A primary winding of 730 turns of single polyurethane coated #42 AWG copper wire is formed on a ceramic rod 3/16 inch in diameter by 1 3/16 inches long. Input and output leads 1½ inches long are provided and a tap is brought out at 318 turns. A ½ inch wide, .00025 inch thick tape of polytetrafluoroethelene is wound over the primary winding with 20% overlap at the tape edges.

The ground winding, of single polyurethane coated #40 AWG copper wire, is coiled over the taped primary winding. Approximately 550 turns, having taps every 24 turns, are provided. One tap of each section is soldered to a ground plane conductor of ⅛ inch wide x 2 inches long, 1¼ mil tinned copper foil.

Accordingly a line having a total delay of 405 nanoseconds and a tap delay of 225 nanoseconds is provided with a rise time "in" of 25 nanoseconds and "out" of 55 nanoseconds. The rated voltage is 400 v. DC; the impedance is 500 ohms; and the attenuation is 15% max.

EXAMPLE II

A primary winding of uncoated tri-filar 33 AWG copper wire and 38 AWG heavy polyurethane coated wire is formed on a ceramic rod ⅛ inch in diameter and 12½ inches long. Sufficient windings are provided to establish a primary winding of close wound turns 12 inches in length. Insulation between turns is provided by winding the wires simultaneously, beside one another, with the covered wire insulating adjacent turns. This winding is covered wth polytetrafluoroethelene tape to a thickness of 1½ mils.

A castellated metallized film is utilized, in this example, as a ground winding. The film is 1¼ mil copper deposited on a 2 mil polytetrafluoroethelene sheet. A number of .005 inch separations extend from one edge of the 12 inch long film to provide ⅛ inch wide x 1 inch long castellations. The ground winding consists of three turns of the film with the copper on the inside adjacent the tape insulation of the primary winding. The uncastellated edge extends from the winding to provide a ground plane conductor.

This construction provides a line having an 8 nanosecond delay, a line rise of 6 nanoseconds "out" with less than 1 nanosecond "in" and an attenuation of approximately 10%. The rated voltage is 500 volts and the line impedance is 93 ohms.

Obviously many modifications and variations of the present invention are possible in the light of the above teachings. It is, therefore, to be understood that within the scope of the appended claims, the invention may be practiced otherwise than as specifically described.

What is claimed:

1. A delay line having a principal winding of turns of an electrical conductor, a plurality of ground winding sections of turns of an electrical conductor wound re-

spectively in close capacitive and inductive linkage with successive portions of the principal winding, adjacent windings and adjacent turns of each winding being insulated from each other, each ground winding section having a corresponding and electrically connected to a common ground plane conductor, and having the opposing end unconnected, a pair of input terminals for applying an input signal between one end of the principal winding and ground, and a pair of output terminals for removing the delayed signal from the other end of the principal winding.

2. The combination of claim **1** in which a layer of dielectric separates the primary winding from the ground winding sections.

3. The combination of claim **1** in which the conductor of said ground winding sections is multi-filar and the principal winding is uninsulated bi-filar wire separated by a single strand of insulated wire and wherein a plurality of strands of the ground winding lie within each hollow formed between turns of the principal winding end, thereby causing a peak capacitive density between the windings.

4. The combination of claim **1** in which the ground winding sections are wound around the principal winding.

5. The combination of claim **1** in which the principal winding is wound around the ground winding sections.

6. The combination of claim **1** in which the delay line is formed about a coil form having high permeability elements incorporated in the coil form.

7. The combination of claim **1** wherein the ground windings are each wound in the direction opposite that of the principal winding.

8. A delay line having a principal winding of turns of electrical conductor closely wound with a plurality of taps at least a few turns apart from each other, a plurality of ground winding sections of turns of electrical conductor coaxially wound in capacitive and inductive linkage over successive portions of the principal winding, adjacent windings and adjacent turns being insulated from each other, the ground windings being each wound in the direction opposite that of the principal winding, each ground winding section having a corresponding end electrically connected to a common ground plane conductor and having the opposing end unconnected.

9. The combination of claim **8** wherein the principal winding and the ground winding sections are of insulated copper wire and wherein each ground section is substantially identical to each other and are all one to three times longer than the principal winding diameter.

10. A delay line comprising a principal winding of turns of an electrical conductor with adjacent turns of the winding insulated from each other, a metallized film comprising a dielectric base and a plurality of metal castellations on its surface, the film wound convolutely over the principal winding with the dielectric base adjacent the winding, said film having a connection from a common castellation base to a ground plane conductor with the ends of the castellations unconnected, a pair of input terminals for applying an input signal between one end of the principal winding and ground, and a pair of output termials for removing the delayed signal from the other end of the principal winding.

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