Nov. 23, 1965 H. BRUECKMANN 3,219,950

LOW-LOSS CONTINUOUSLY VARIABLE DELAY LINE

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FIG. 1

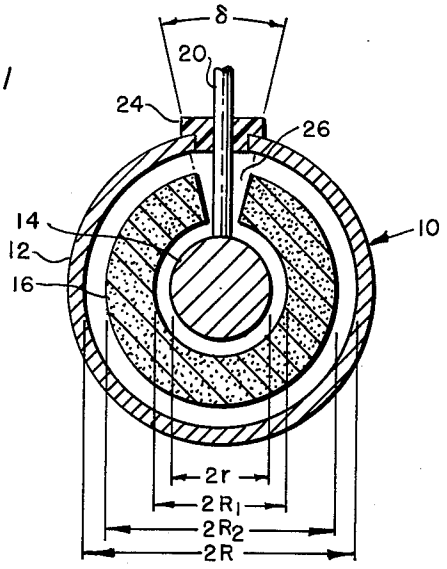


FIG. 2

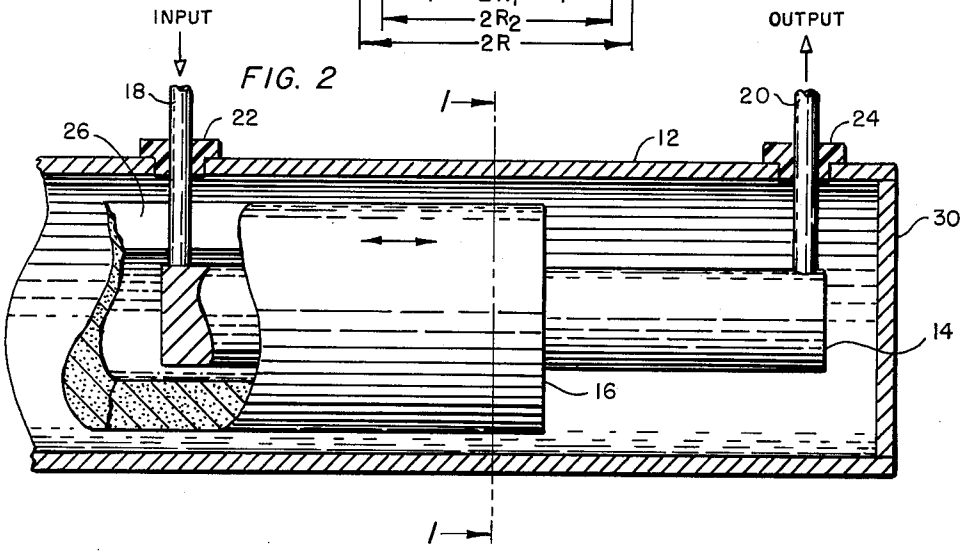
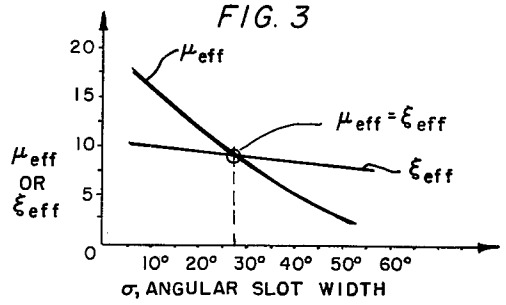


FIG. 3



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FIG. 4

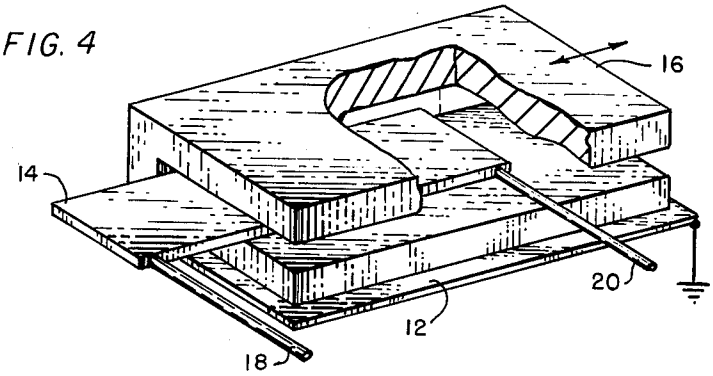


FIG. 5

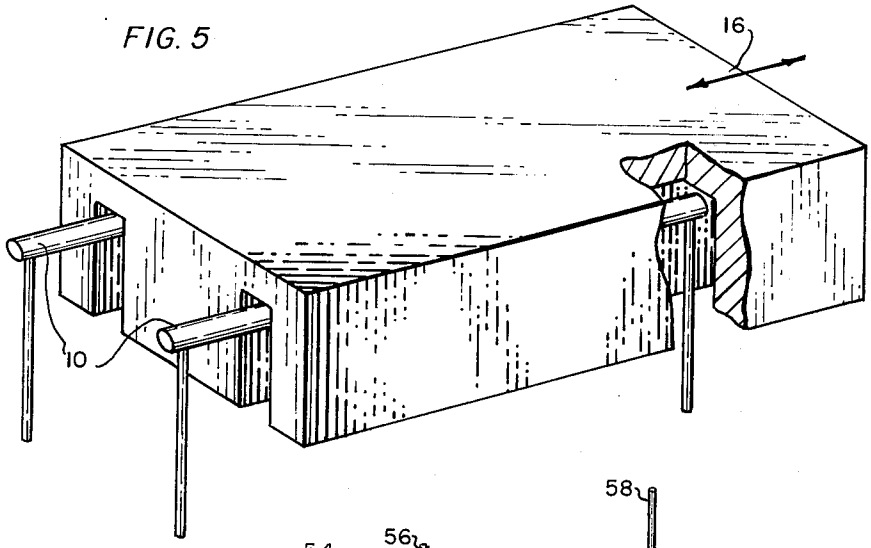
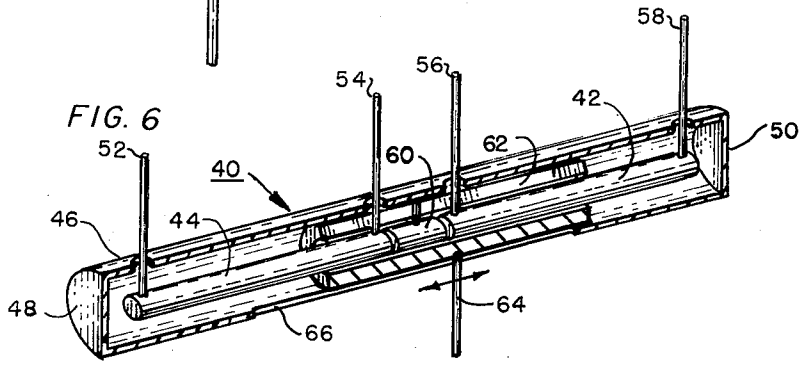


FIG. 6



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LOW-LOSS CONTINUOUSLY VARIABLE DELAY LINE

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11 Claims. (Cl. 333—31)
(Granted under Title 35, U.S. Code (1952), sec. 266)

The invention described herein may be manufactured and used by or for the Government for governmental purposes without the payment of any royalty thereon.

This invention relates to delay lines and more particularly to a low-loss, continuously variable, delay line for use in RF frequencies at high power levels.

One type of variable delay line well known in the art is essentially a helical transmission line provided with a sliding contact. This type of variable delay line is characterized by high losses unless it is made of thick wire, in which case it becomes rather heavy and bulky. Also, the sliding contacts are a potential source of trouble, particularly in applications involving high RF power, and the delay does not vary continuously. Other types of known high-frequency variable delay lines are limited in their use by one of the above mentioned factors.

It is an object of the present invention to provide an improved delay line wherein the aforementioned limitations are overcome.

It is another object of the present invention to provide an improved continuously variable delay line which has no contacts of any sort and permits the use of large size conductors.

In brief, there is provided a continuously variable, low-loss delay line which includes a transmission line section comprising a pair of conductors and a ferrite dielectric adapted to be slidably positioned relative to the conductors. The parameter of the ferrite dielectric is chosen such that the characteristic impedance of the transmission line remains constant regardless of the relative position of the ferrite dielectric with respect to the conductors. The ferrite dielectric is slidably positioned with respect to the conductors such that in one extreme position, the ferrite dielectric is coextensive with the conductors, and in the other extreme position, the ferrite dielectric is completely removed from the spacing between the conductors and replaced by an air dielectric. The delay of an RF signal applied to the transmission line may be continuously varied between a minimum delay produced when the ferrite dielectric is completely removed, and a maximum delay when the ferrite dielectric is coextensive with the conductors.

For a better understanding of the invention, together with other and further objects thereof, reference is had to the following description taken in connection with the accompanying drawings in which:

FIGS. 1 and 2 are end and side sectional views, respectively, of a delay line according to the teachings of the invention with FIG. 1 being a sectional view along the lines 1—1 of FIG. 2;

FIG. 3 is a graph useful in designing the delay line shown in FIGS. 1 and 2; and

FIGS. 4, 5 and 6 illustrate other embodiments of the present invention.

Referring now to FIGS. 1 and 2 of the drawing, there is shown at **10** a coaxial-type transmission line section having an outer conductor **12**, an inner conductor **14** and a tubular ferrite dielectric **16**. The inner conductor **14** is supported and held fixed at its ends by a pair of longitudinally spaced, parallel-arranged, radial conductors **18** and **20** which extend through and are affixed to insulator plugs **22** and **24** respectively provided therefor. As

shown, insulator plugs **22** and **24** are affixed to outer conductor **12** to form an integral part thereof. Tubular ferrite dielectric **16** is provided with a longitudinal slot **26** having a width slightly larger than the width of radial conductors **18** and **20** so that the ferrite dielectric **16** may be longitudinally actuated along the axis of the transmission line. The ferrite dielectric **16** is concentrically positioned with respect to outer and inner conductors **12** and **14** and is spaced therefrom so that an air space exists between the inner longitudinal periphery of tubular ferrite **16** and inner conductor **14**, and also between the outer longitudinal periphery of ferrite **16** and outer conductor **12**. The surfaces bounding longitudinal slot **26** are shown in FIG. 1 as being radial and include the angle δ therebetween. With the slot **26** aligned with the radial conductors **18** and **20**, the ferrite dielectric **16** may be slidably positioned along the longitudinal axis of the coaxial line section **10** so that the spacing between the inner and outer conductors **14** and **12** includes all of ferrite dielectric **16** when it is in one extreme longitudinal position, and only air separates the two conductors **12** and **14** when the ferrite dielectric **16** is at its other extreme longitudinal position. Of course, any suitable means well known in the art may be used to slidably position ferrite dielectric **16** longitudinally intermediate the outer and inner conductor of line **10** as described above. The high-frequency input signals to be delayed are applied to coaxial section **10** through radially disposed conductor **18** and the delayed output signal is derived from radially disposed conductor **20**. As shown, the outer conductor **12** is terminated at the output end of the line by a metallic plate **30** which is spaced from the end of inner conductor **14**. The spacing is chosen such that the lumped capacity due to end plate **30** and the lump inductance of radial conductor **20** effectively comprise a π type filter having a characteristic impedance which matches that of the coaxial line section **10**. Electrically, this is equivalent to a low pass filter circuit having a cutoff frequency above the operating signal frequency range. The dimensions of the line shown in FIG. 1 are shown to be $2r$ for the diameter of the inner conductor **14**; $2R_1$ for the inner diameter of ferrite dielectric tube **16**; $2R_2$ for the outer diameter of ferrite dielectric tube **16**; 2R for the inner diameter of outer conductor **12**; and δ the angle included between the radially arranged peripheral surfaces bounding slot **26**. Although the ferrite material within the line **10** has been termed a "dielectric," it should be noted that this material also has magnetic properties since its relative permeability is greater than unity; and it is the combination of its dielectric and magnetic properties which affect the parameters of a line containing ferrite. The arcuate or circumferential spacing of the slot **26** is so chosen that the characteristic impedance of the line does not change regardless of the relative position of the tubular ferrite dielectric **16** with respect to the outer and inner conductors **12** and **14**. This will occur when the effective relative permeability μ_{eff} and the effective relative dielectric ϵ_{eff} of line section **10** are equal when the air spacing between the inner and outer conductors is replaced by ferrite dielectric **16**. However, the propagation velocity relative to light velocity C is reduced in accordance with the following equation

$$\frac{V}{C}=\frac{1}{\sqrt{\mu_{eff}\cdot\epsilon_{eff}}} \qquad (1)$$

This means, of course, that a variable delay may be obtained by first having the ferrite dielectric tube **16** coextensive with and intermediate the outer and inner conductors **12** and **14** of line **10**, and then gradually moving the ferrite tube longitudinally from the line until it is completely removed therefrom. The delay can thus be varied continuously between a minimum delay which is produced

in the latter case and a maximum delay which is produced in the former case when the ferrite dielectric is completely within coaxial line section **10**.

The following mathematical analysis will provide a better understanding of the operation of the invention. Using the dimensions shown in FIGS. 1 and 2, it can be shown that

$$\mu_{eff}=\left[\frac{\mu_r}{1+\frac{\delta}{2\pi}(\mu_r-1)}-1\right]\frac{ln\frac{R_2}{R_1}}{ln\frac{R}{r}}+1 \qquad (2)$$

where μ_r is the relative permeability of the ferrite. This relation shows that the relative effective permeability is considerably smaller than the relative permeability of ferrite dielectric even if the slot is only a small fraction of the circumference of the conductors **12** and **14**. The effective dielectric constant of the line is also smaller than the relative dielectric constant ϵ_r of the ferrite dielectric and can be shown to be

$$\epsilon_{eff}=\frac{\left(1-\frac{\delta}{2\pi}\right)ln\frac{R}{r}}{ln\frac{R_1}{r}+\frac{1}{\epsilon_r}ln\frac{R_2}{R_1}+ln\frac{R}{R_2}}+\frac{\delta}{2\pi} \qquad (3)$$

It can be seen from Equations 2 and 3 that both μ_{eff} and ϵ_{eff} are functions of the slot width δ. FIG. 3 shows a plot of μ_{eff} and ϵ_{eff} according to Equations 2 and 3 as a function of the slot width δ for a commercially available ferrite known as Q² and characterized by a μ_r=41 and an ϵ_r=11. For reasons of simplicity, the clearance between the ferrite dielectric **16** and the outer and inner conductors **12** and **14** has been neglected. In FIG. 3, the ratio of the outer and inner radii R/*r* of line **10** was arbitrarily chosen so that the characertistic impedance of the line **10** without the tubular ferrite dielectric **16** is 60 ohms. As shown in FIG. 3, $\mu_{eff}=\epsilon_{eff}$ at the point the curves cross and, with the other above mentioned parameters, this point was achieved when δ=27°. This means, of course, that a slot width of about 27° results in a line whose characteristic impedance does not change when the tubular ferrite dielectric body is removed and accordingly replaced by air dielectric. However, the propagation velocity V relative to the light velocity C is reduced in accordance with Equation 1. Thus, for example, a ten nanosecond delay, which corresponds to 180° phase shift at 50 mc., requires a ferrite body length of only 30 cm. completely within the coaxial line section. The delay is reduced to one nanosecond, which corresponds to 18° phase shift at 50 mc., when the ferrite body is completely removed from the coaxial line section. Between the limits of one and 10 nanoseconds, of course, the delay is continuously variable.

Although the slot width of the line shown in FIG. 1 is angular, that is, bounded by radially disposed surfaces, it need not be so limited. A slot of uniform width for example may be utilized and the relationship of the values of μ_{eff} and ϵ_{eff} to the slot width can be established empirically or theoretically. A uniform slot width has the advantage of resulting in a more uniform flux density versus radius in the ferrite and thus increase the power handling capacity of the line if it is limited by hysteresis losses alone.

FIGS. 4 and 5 illustrate the strip-line and two wire line embodiment, respectively, of the present invention. Like reference numerals refer to like parts. In FIG. 4, the ferrite dielectric **16** is shown as being slidably positioned with respect to the conductor **14** which is parallel to ground plane **12** of the strip-line. In FIG. 5, the ferrite dielectric **16** is shown as being slidably positioned with respect to the two wire transmission line **10**. While the provision necessary to hold the conductors in place and yet permit sliding the ferrite dielectric body into and out of the transmission line section may initially cause an excess of capacitance and inductance at the terminals, such discontinuities may be compensated for by conventional techniques such as appropriate changes in conductor spacing and/or conductor size.

FIG. 6 illustrates an embodiment of the invention wherein two delay lines are combined "back-to-back" to provide a differential delay line. Referring now to FIG. 6, there is shown at **40** a coaxial line section which has two axially spaced aligned and colinear inner conductors **42** and **44** and a common outer conductor **46** terminated by end plate conductors **48** and **50**. As in FIGS. 1 and 2, the end plates **48** and **50** are appropriately spaced from the ends of inner conductors **44** and **42** respectively. Spaced radial conductors **52** and **54** support inner conductor **44** within line **40** and similarly spaced radial conductors **56** and **58** support inner conductor **42** within line **40**. As in FIGS. 1 and 2, all the radial conductors are linearly aligned. A metallic cylinder **60** is axially positioned intermediate the inner conductors **42** and **44** in order to isolate or decouple one line from the other. The tubular ferrite dielectric **62** is disposed intermediate the inner conductors **42** and **44** and is spaced therefrom as described in connection with FIGS. 1 and 2. Ferrite dielectric **62** is provided with a longitudinal slot for its entire length so that it can be axially and longitudinally positioned within the coaxial line section **40** by any suitable means as represented by the rod **64**. The embodiment illustrated in FIG. 6 may be used to delay one signal relative to another, also controllable signal, hereinafter referred to as the "reference" signal. The reference signal is transmitted through one section of line **40** and the other signal is transmitted through the other section of line **40**. By longitudinally positioning tubular ferrite dielectric **62**, the delay in one section of line is increased by a certain amount and the delay in the other section is decreased by the same amount, and vice versa. The net result is that the maximum difference in delay is doubled, yet the space occupied by the line of FIG. 6 is only slightly larger than that occupied by the single delay line illustrated in FIGS. 1 and 2.

In the embodiments described above the ferrite dielectric is shown as composed of a solid ferrite dielectric material. From an electrical viewpoint, the ferrite body may comprise alternating slices of ferrite material and ceramic having a high dielectric constant. If the slices are made so thin that their electrical length is smaller than about 1/12 of the wavelength of the ferrite at the highest operating frequency, the line still acts as a uniform line. The effective permeability and the effective dielectric constant in this arrangement are simply the weighted averages of the respective values of the materials. With this arrangement the average dielectric constant with the stacked slices can be raised to any desired value.

While there has been described what is at present considered to be the preferred embodiment 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 continuously variable, low-loss delay line comprising a pair of conductors, a ferrite dielectric intermediate said conductors, said ferrite dielectric being adapted to be slidably positioned with respect to said conductors such that when in one extreme position the ferrite dielectric and said conductors are coextensive, and when in the other extreme position, the ferrite dielectric is completely removed from the spacing between said conductors and replaced by an air dielectric, the effective relative permeability μ_{eff} and the effective relative dielectric ϵ_{eff} being equal when the air spacing between said conductors is replaced by said ferrite dielectric.

2. The delay line in accordance with claim **1** wherein said conductors comprise a strip-line.

3. A continuously variable, low-loss delay line comprising a transmission line section for propagating an RF signal including an inner conductor and an outer conductor coaxial therewith, a tubular ferrite dielectric adapted to be axially positioned intermediate said conductors such that when in one extreme position the ferrite dielectric and said conductors are coextensive, and when in the other extreme position, the ferrite dielectric is completely removed from the spacing between said conductors and replaced by an air dielectric, said tubular ferrite including a longitudinal slot, the width of said slot being such that the characteristic impedance of said transmission line section remains constant regardless of the relative axial position of the tubular ferrite dielectric between said inner and outer conductors.

4. The delay line in accordance with claim 3 wherein the tubular ferrite dielectric is spaced from both said inner and outer conductors when intermediate said conductors.

5. The delay line in accordance with claim 3 wherein the tubular dielectric is spaced from both said inner and outer conductors intermediate said conductors.

6. The delay line in accordance with claim 5 wherein said outer conductor is terminated at one end by a plate axially spaced from said inner conductor.

7. A continuously variable, low-loss delay line comprising a transmission line section including an inner conductor and an outer conductor coaxial therewith, respective RF input and output radial conductors affixed to the respective ends of said inner conductor, said radial conductors being linearly aligned and extending through said outer conductor and insulated therefrom, a tubular ferrite dielectric having a longitudinal slot and adapted to be axially positioned intermediate said inner and outer conductors, said slot being aligned with said radial conductors, the width of said slot being such that the characteristic impedance of said transmission line section remains constant when any portion of the air spacing between said inner and outer conductors is replaced by said ferrite dielectric.

8. The delay line in accordance with claim 7 wherein said outer conductor is terminated at the output radial conductor end by a plate axially spaced from said inner conductor.

9. A continuously variable, low-loss delay line comprising a transmission line section including an inner conductor and an outer conductor coaxial therewith, respective RF input and output radial conductors affixed to the respective ends of said inner conductor, said radial conductors being linearly aligned and extending through said outer conductor and insulated therefrom, a tubular ferrite dielectric having a longitudinal slot and adapted to be axially positioned intermediate said inner and outer conductors, said slots being aligned with said radial conductors and bounded by radially disposed surfaces including an angle δ therebetween, said angle δ having a value such that the characteristic impedance of said transmission line section remains constant when any portion of the air spacing between said inner and outer conductors is replaced by said ferrite dielectric.

10. A continuously variable, low-loss delay line comprising a transmission line section for propagating an RF signal and including an inner conductor and an outer conductor coaxial therewith, a tubular ferrite dielectric spaced from both said inner and outer conductors and adapted to be axially positioned intermediate said conductors such that when in one extreme position the ferrite dielectric and said conductors are coextensive, and when in the other extreme position the ferrite dielectric is completely removed from the spacing between said conductors and replaced by an air dielectric, the effective relative permeability μ_{eff} and the effective relative dielectric ϵ_{eff} of said line being equal when the air spacing between said conductors is replaced by said ferrite dielectric.

11. The delay line in accordance with claim 10 wherein the ferrite dielectric comprises alternating pieces of a ferrite material and a ceramic having a high dielectric constant.

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