

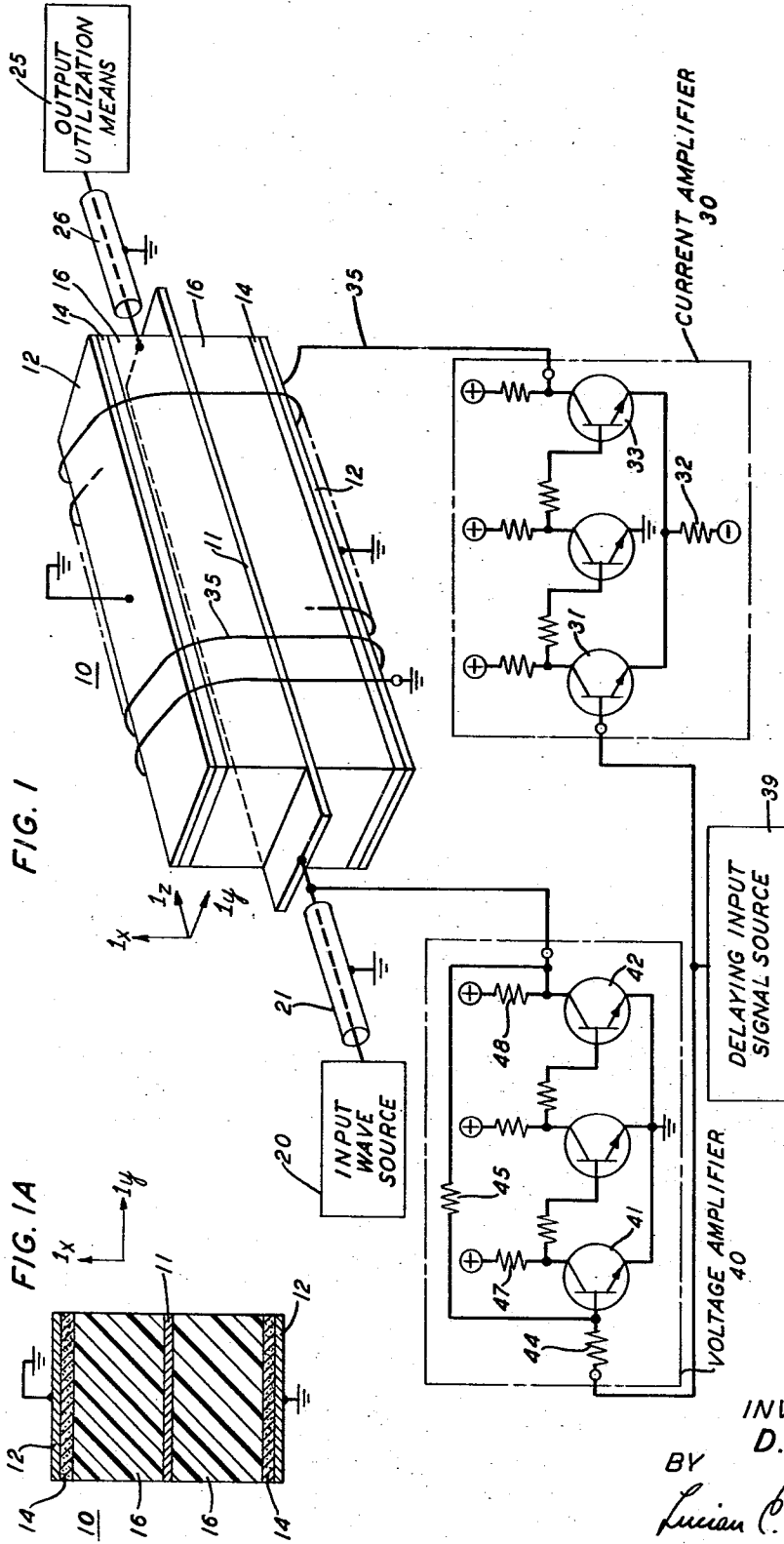
Sept. 26, 1967

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ELECTROMAGNETIC WAVE DELAYING ARRANGEMENT  
WITH CONSTANT ITERATIVE IMPEDANCE

3,344,366

Filed June 3, 1964

2 Sheets-Sheet 1



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FIG. 2

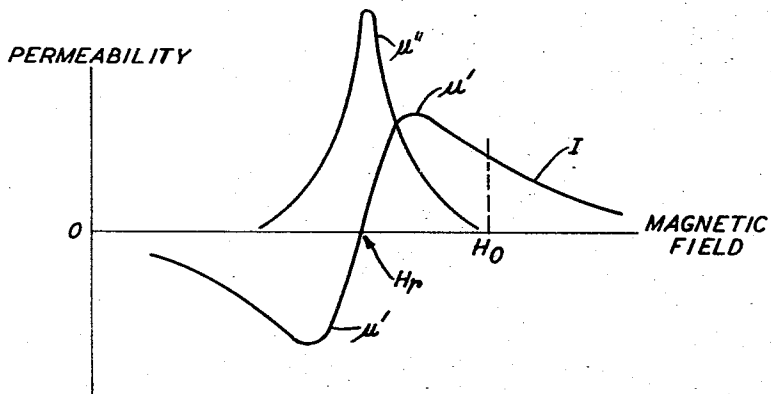
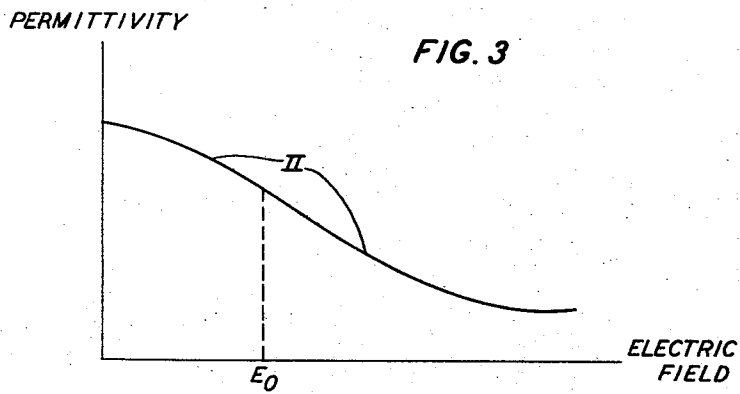


FIG. 3



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**ELECTROMAGNETIC WAVE DELAYING ARRANGEMENT WITH CONSTANT ITERATIVE IMPEDANCE**

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1 Claim. (Cl. 333—31)

This invention relates to electromagnetic wave propagating arrangements and, more specifically, to a circuit combination which delays an input wave for a variable time interval.

A plurality of electromagnetic wave transmission embodiments, such as coaxial cables, waveguides and strip lines, are employed in high frequency systems to propagate wave energy. To effect various desired circuit operations in the frequency spectrum of interest, prior art transmission structures have been loaded with ferromagnetic and/or dielectric materials to employ the bulk properties of these substances. In addition, an external magnetic field has been utilized to bias the ferromagnetic material of such a structure to a particular value of permeability.

However, prior transmission embodiments loaded in the above-described manner are characterized by variable iterative impedance which gives rise to undesired wave reflections in the circuit elements associated therewith.

It is therefore an object of the present invention to provide an improved electromagnetic wave delaying arrangement.

More specifically, an object of the present invention is the provision of a wave delaying arrangement which comprises a constant characteristic impedance for a range of time delaying intervals.

It is another object of the present invention to provide a wave delaying embodiment which may be relatively simply and inexpensively fabricated, and which is highly reliable.

These and other objects of the present invention are realized in a specific, illustrative, electronically variable electromagnetic wave delaying arrangement which is characterized by a constant iterative impedance for any selected time delay. The embodiment includes a wave transmission structure which is loaded with a ferromagnetic thin film and a dielectric material characterized by a permittivity which is a function of an externally-applied electric field.

The thin film and dielectric material are respectively biased to desired quiescent values of permeability and permittivity by current and voltage amplifiers coupled thereto. The current and voltage amplifiers are adapted to respond to a common input signal by generating like percentage changes in the film permeability and the permittivity of the electric field responsive material.

Since the product of the film permeability with the dielectric permittivity is variable, while their quotient is constrained to remain constant, the instant arrangement comprises a constant characteristic impedance for any selected wave delaying time interval.

It is thus a feature of the present invention that an electromagnetic wave delaying arrangement include a wave transmission embodiment loaded with a ferromagnetic thin film and a dielectric material characterized by a permittivity which is a function of an external electric field, sources for respectively biasing the film and the dielectric material to quiescent values of permeability and permittivity, and circuit elements for effecting like percentage changes in the film permeability and the dielectric permittivity.

It is another feature of the present invention that a wave delaying arrangement include a wave propagation structure loaded with a ferromagnetic thin film and an electric field responsive dielectric material, a variable voltage source coupled to the dielectric, a winding coupled to the thin film and a variable current source connected to the winding, and circuit elements connected to the current and voltage sources for effecting like percentage changes in the permeability and permittivity respectively characterizing the thin film and the dielectric material.

A complete understanding of the present invention, and of the above and other features, advantages and variations thereof may be gained from a consideration of the following detailed description of an illustrative embodiment thereof presented hereinbelow in conjunction with an accompanying drawing, in which:

FIG. 1 is a schematic diagram of an illustrative electromagnetic wave delaying arrangement made in accordance with the principles of the present invention;

FIG. 1A is a cross-sectional diagram of a wave propagating structure included in FIG. 1;

FIG. 2 illustrates the relationship between the permeability of a ferromagnetic thin film included in FIG. 1 and the applied magnetic field; and

FIG. 3 illustrates the relationship between the permittivity of a dielectric material included in FIG. 1 and the applied electric field.

Referring now to FIG. 1, there is shown a specific, illustrative, electronically variable electromagnetic wave delaying arrangement which is characterized by a constant iterative impedance for any selected time delay. The arrangement includes a wave propagating structure 10 comprising a center conducting sheet 11 and two grounded conducting planes 12 on either side of the sheet 11. Between the center conductor 11 and each of the grounded planes 12 there is interposed a ferromagnetic thin film 14 and a dielectric material 16 which is characterized by a permittivity which varies with the applied electric field. The particular organization of the propagating structure 10, which is known as a strip line, is illustrated in cross-sectional form in FIG. 1A.

Ferromagnetic thin films are well known in the art and described, for example, in an article by E. M. Bradley entitled, "Making Reproducible Magnetic-Film Memories," published at page 78, et seq., of Electronics Magazine, Sept. 9, 1960. The dielectric material employed in FIG. 1 may advantageously comprise any ferroelectric substance which is operated at a temperature above its Curie point. In this temperature range, such materials are characterized by a large field-dependent induced polarization. Specifically, a combination of 73% barium titanate ( $\text{BaTiO}_3$ ) and 27% strontium titanate ( $\text{SrTiO}_3$ ), which form a ceramic composition, may be employed.

An input wave source 20 is included in the FIG. 1 arrangement to supply electromagnetic wave energy to the input end of strip line 10 via a coaxial cable 21. Similarly, a coaxial cable 26 is employed to connect the output end of the line 10 to an output utilization means 25. A delaying input signal source 39 is connected to the input terminal of a three-stage, shunt feedback operational voltage amplifier 40 which has the output thereof joined to the junction between the strip line center conductor 11 and the coaxial cable 21. The amplifier 40 includes an input transistor 41 and an output transistor 42 respectively having their collectors connected via load resistors 47 and 48 to positive potential sources, with the emitters of these devices being grounded. Finally, an input resistor 44 is connected between the amplifier input terminal and the base of the transistor 41, and a shunt feedback resistor 45 connects the collector of the output transistor 42 with the base of the input transistor 41.

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When a voltage  $v_d(t)$  is supplied to the input terminal of the amplifier 40 by the delaying input signal source 39, a voltage  $v_o(t)$  is supplied by the collector of the output transistor 42 to the strip line center conductor 11, where

$$v_o(t) = v_d(t) \cdot \frac{R_{45}}{R_{44}} \cdot \frac{A}{1+A} \quad (1)$$

wherein  $R_{44}$  and  $R_{45}$  are the resistance values of the elements 44 and 45, respectively, and  $A$  is the loop gain of the amplifier 40. Since the loop gain  $A$  is relatively high for three cascaded transistor stages, the output voltage  $v_o(t)$  may be closely approximated by

$$v_o(t) = v_d(t) \frac{R_{45}}{R_{44}} \quad (2)$$

Hence, the over-all gain  $G_{40}$  of the amplifier 40 is

$$G_{40} = \frac{v_o(t)}{v_d(t)} = \frac{R_{45}}{R_{44}} \quad (3)$$

A winding 35 is coupled to the strip line 10 along its long dimension, which corresponds to the direction given by a unit vector  $\mathbf{1}_z$  illustrated in FIG. 1. The winding 35 is driven by a current amplifier 30 which has the input terminal thereof connected to the delaying input signal source 39. The circuit combination 30 comprises a three-stage, series feedback amplifier including an input transistor 31 and an output transistor 33. Series current feedback is provided by a resistor 32 which is connected to the emitter terminals of the transistors 31 and 33.

Since the amplifier 30 includes three stages of forward gain, along with series feedback, this circuit combination effectively acts as a current source with a high output impedance. That is, corresponding to the voltage signal  $v_d(t)$  supplied by the input source 39, the collector of the transistor 33 will supply a current  $i_o(t)$  to the winding 35 wherein

$$i_o(t) = \frac{v_d(t)}{R_{32}} \frac{A'}{1+A'} \quad (4)$$

with  $R_{32}$  being the resistance value of the element 32, and where  $A'$  comprises the loop gain of the feedback amplifier 30. Since the loop gain  $A'$  is relatively large for three transistor stages,  $i_o(t)$  is approximately given by

$$i_o(t) = \frac{v_d(t)}{R_{32}} \quad (5)$$

Hence, it is observed from the above that the current amplifier 30 essentially functions as a voltage-to-current converter, with a gain  $G_{30}$  given by

$$G_{30} = \frac{i_o(t)}{v_d(t)} = \frac{1}{R_{32}} \quad (6)$$

In order to completely illustrate the operation and novel features of the present invention, expressions for the velocity of a wave propagating down the strip line 10, and the characteristic impedance of the line 10 are required. As a starting point, Maxwell's equations for the charge free region between the strip line center conductor 11 and each of the conducting planes 12 are given by

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} \quad (7)$$

and

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (8)$$

where  $\mathbf{H}$ ,  $\mathbf{D}$  and  $\mathbf{E}$ , respectively, represent the magnetic field intensity, the displacement density and the electric field intensity. Employing the well known relationships

$$\mathbf{D} = \epsilon \mathbf{E} \quad (9)$$

and

$$\mathbf{B} = \mu \mathbf{H} \quad (10)$$

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then Equations 7 and 8 above may be rewritten

$$\nabla \times \mathbf{H} = \epsilon \frac{\partial \mathbf{E}}{\partial t} \quad (11)$$

5 and

$$\nabla \times \mathbf{E} = \frac{1}{\mu} \frac{\partial \mathbf{H}}{\partial t} \quad (12)$$

where  $\mu$ ,  $\epsilon$  and  $\bar{E}$ , respectively, represent the permeability and permittivity of the medium between the center and outer conductors 11 and 12, and the magnetic field density.

When the input source 20 supplies an electromagnetic wave to the strip line 10, an electric field component  $E_x$  and a magnetic field component  $H_y$  are respectively induced in the regions between the center conductor 11 and the grounded planes 12, where the  $x$  and  $y$  directions are indicated by the unit vectors  $\mathbf{1}_x$  and  $\mathbf{1}_y$  illustrated in FIGS. 1 and 1A. It is noted that no electric field component exists in either the  $y$  or  $z$  directions, and that there is no magnetizing field component in either of the  $x$  or  $z$  directions. Moreover, the electric and magnetic fields  $E_x$  and  $H_y$  are solely functions of time and of the  $z$  coordinate. As is well known, the aforementioned field components define a wave propagating down the strip line 10 in the transverse electromagnetic (T.E.M.) mode.

Evaluating the curl in Equation 11 by

$$\nabla \times \mathbf{H} = \begin{vmatrix} \mathbf{1}_x \mathbf{1}_y \mathbf{1}_z \\ \frac{\partial}{\partial x} \frac{\partial}{\partial y} \frac{\partial}{\partial z} \\ H_x H_y H_z \end{vmatrix} \quad (13)$$

and expanding the electric field  $\bar{E}$  in accordance with the expression

$$\bar{E} = E_x \mathbf{1}_x + E_y \mathbf{1}_y + E_z \mathbf{1}_z \quad (14)$$

then Equation 11 in the system defined above and evaluated in either region between the center conductor 11 and one of the grounded planes 12 yields

$$-\frac{\partial H_y}{\partial z} \mathbf{1}_x = \epsilon \left( \frac{\partial E_x}{\partial t} \mathbf{1}_x + \frac{\partial E_y}{\partial t} \mathbf{1}_y + \frac{\partial E_z}{\partial t} \mathbf{1}_z \right) \quad (15)$$

Equating the two vectors in the  $x$  direction results in

$$\frac{\partial H_y}{\partial z} = -\epsilon \frac{\partial E_x}{\partial t} \quad (16)$$

In a corresponding fashion, beginning with Equation 12 and expanding the curl of the electric field  $\bar{E}$  by the determinant method analogous to Equation 13,

$$\frac{\partial E_x}{\partial z} = -\mu \frac{\partial H_y}{\partial t} \quad (17)$$

Taking the derivative of Equation 17 with respect to  $z$  yields

$$\frac{\partial^2 E_x}{\partial z^2} = -\mu \frac{\partial}{\partial z} \left( \frac{\partial H_y}{\partial t} \right) \quad (18)$$

Reversing the ordered differentiation on the right side of Equation 18 results in

$$\frac{\partial^2 E_x}{\partial t^2} = \frac{1}{\mu \epsilon} \frac{\partial^2 E_x}{\partial z^2} \quad (19)$$

Equation 19 is the well known wave equation which has for its solution an electric field  $E_x$  given by

$$E_x = f(z - vt) \quad (20)$$

where  $f(z - vt)$  is any function of the argument, where the electric field  $E_x$  is propagating in the  $z$  direction with a velocity  $v$  where

$$v = \frac{1}{\sqrt{\mu \epsilon}} \quad (21)$$

Equation 21 yields the first of two required expressions, and indicates that the velocity of an impressed wave traveling down the strip line 10 is inversely proportional to the square root of the product of the effective per-

meability and permittivity of the medium between the center conductor 11 and an associated grounded plane 12. Note from Equation 21 that the wave velocity  $v$  is a bulk property of the loading materials, and not dependent upon the geometry of the strip line 10.

The characteristic impedance of the strip line 10 is determined by the ratio of the electric and magnetic field wave components, i.e., in the instant case the ratio of  $E_x$  to  $H_y$ . To solve for this product, first take the derivative of  $E_x$  given by Equation 20 with respect to time, such that

$$\frac{\partial E_x}{\partial t} = \frac{\partial f(z-vt)}{\partial(z-vt)} \frac{\partial(z-vt)}{\partial t} = -\frac{v \partial f(z-vt)}{\partial(z-vt)} = -vF' \quad (22)$$

where

$$F' = \frac{\partial f(z-vt)}{\partial(z-vt)} \quad (23)$$

Now taking a partial derivative of  $H_y$  with respect to  $z$  yields

$$\frac{\partial H_y}{\partial z} = -\epsilon(-vF') = \epsilon vF' = \sqrt{\frac{\epsilon}{\mu}} F' \quad (24)$$

Integrating, Equation 24 results in

$$H_y = \sqrt{\frac{\epsilon}{\mu}} \int F' dz \quad (25)$$

Recognize now that

$$\frac{\partial f(z-vt)}{\partial z} = F' \frac{\partial(z-vt)}{\partial z} = F' \quad (26)$$

Substituting the results of Equation 26 in order to effect the integration set forth in Equation 25 yields the resultant expression for  $H_y$  such that

$$H_y = \sqrt{\frac{\epsilon}{\mu}} f(z-vt) \quad (27)$$

Hence, since the characteristic impedance  $Z$  of the strip line is given by

$$Z = \frac{E_x}{H_y} \quad (28)$$

substituting Equations 20 and 27 for  $E_x$  and  $H_y$ , respectively, in Equation 28 generates the final result

$$Z = \frac{f(z-vt)}{\sqrt{\frac{\epsilon}{\mu}} f(z-vt)} = \sqrt{\frac{\mu}{\epsilon}} \quad (29)$$

To recapitulate, it is observed that a wave supplied to the line 10 by the source 20 travels down the line 10 in the  $z$  direction with a velocity dependent upon the product of the effective permeability and permittivity of the medium between the center conductor 11 and the grounded planes 12, while the impedance of the line 10 is a function of the quotient of the permeability and permittivity. As will become apparent from the discussion hereinafter, the FIG. 1 arrangement employs the aforementioned relationships to produce a variable time delay, with no change in the iterative impedance of the line 10.

FIG. 2 illustrates the relationship between the real part  $\mu'$  and the imaginary, orthogonal part  $\mu''$  of the composite permeability  $\mu$  of the thin film 14 and an external magnetic field for a particular signal frequency. The imaginary component of the over-all permeability is a narrow, peaked curve which is symmetrical about a magnetic field  $H_r$ , at which the thin film is ferromagnetic. The permeability component  $\mu'$  is zero at the resonant field  $H_r$ , and characterized by a monotonically decreasing characteristic region (labeled I in FIG. 2) a relatively small distance to the right of the field  $H_r$ . The magnitude of the permeability  $\mu$  is given by

$$\mu = \sqrt{(\mu')^2 + (\mu'')^2} \quad (30)$$

and, since the imaginary component  $\mu''$  is relatively small at values of magnetic field corresponding to the region I

of the  $\mu'$  characteristic, in this range to a good approximation

$$\mu = \mu' \quad (31)$$

FIG. 3 illustrates the relationship between the permittivity of a typical dielectric material, e.g., barium-strontium titanate, and an external electric field. Note that the characteristic includes a portion II in which the permittivity is a monotonically decreasing function of the applied field. It is noted that the permittivity of the dielectric material is much higher than the permittivity of the film and, correspondingly, the permeability of the film far exceeds the permeability of the ceramic. Hence, the effective permittivity and permeability for the composite medium between the center conductor 11 and the grounded planes 12 of the strip line 10 essentially corresponds to dielectric permittivity and film permeability.

With the above circuit organization and material properties in mind, the operation of the FIG. 1 delaying arrangement will now be described. In typical circuit functioning, the strip line 10 advantageously comprises a characteristic impedance equal in magnitude to the input impedance of the output utilization means 25 in order to effect a power match and avoid energy reflections. Hence, the delaying input signal source 39, the current amplifier 30 and the voltage amplifier 40 are adapted to generate a quiescent magnetic field  $H_0$  and quiescent electric field  $E_0$ , respectively shown in FIGS. 2 and 3, such that the corresponding strip line permeability and permittivity produce the desired iterative impedance, as determined from Equation 29. The quiescent delay generated by the FIG. 1 arrangement under this set of circuit conditions is given by the quotient of the length of the strip line 10 and the propagation velocity which is determined by inserting the appropriate initial values of  $\mu$  and  $\epsilon$  in Equation 21.

When a larger delaying interval is desired, the direct current input voltage signal supplied by the source 39 is decreased from its quiescent value. Responsive thereto, the voltage amplifier 40 supplies a smaller voltage and thereby also a decreased electric field to the dielectric material. Similarly, the current amplifier 30 responds to the decreased delaying input signal from the source 39 by supplying a smaller value of current to the winding 35, thereby also supplying a decreased magnetic field to the thin film 14. As noted from FIGS. 2 and 3, both the film permeability and the dielectric permittivity are increased when the applied magnetic and electric fields are decreased. Examining Equation 21, note that such a change in permeability and permittivity effectively slows down the propagation of an input wave through the strip line 10, thereby increasing the wave delaying interval. Hence, the desired operation is accomplished.

Moreover, the transfer characteristics of the amplifiers 30 and 40, respectively, given by Equations 5 and 3, are advantageously adapted to respond to the decreased input signal from the source 39 by effecting like percentage changes in the bulk properties of the thin film 14 and dielectric 16. That is, the ratio of the film permeability to the dielectric permittivity remains constant and equal to the previous value corresponding to the external fields  $E_0$  and  $H_0$ . Hence by reason of the line impedance relationship given in Equation 29, the increased time delay produced by the strip line 10 does not alter the iterative impedance thereof, and the line remains matched to the input impedance of the output utilization means 25.

In a similar manner, if a shorter time delay is desired, the delaying input source 39 is adapted to supply a potential greater than the quiescent value, thereby causing the amplifiers 30 and 40 to generate magnetic and electric fields which exceed  $H_0$  and  $E_0$  in magnitude. Referring to FIGS. 2 and 3, it is seen that under these conditions the film permeability and the dielectric permittivity are each decreased. Thus, by again examining Equation 21, the wave velocity for the instant circuit condition is

caused to increase, and therefore the signal applied to the strip line 10 by the input source 20 propagates down the line in the z direction in a shorter time interval than was heretofore the case. However, as before, the ratio of permeability to permittivity remains constant, and hence no undesired reflections are generated by the line 10.

Thus, the FIG. 1 arrangement has been shown to electronically vary the propagation time of a signal supplied by the source 20 to the output utilization means 25. In addition, the line 10 maintained a constant characteristic impedance independent of the specific delaying interval.

Summarizing the basic concepts of an illustrative embodiment of the present invention, an electronically variable electromagnetic wave delaying arrangement is characterized by a constant iterative impedance for any selected time delay. The embodiment includes a wave transmission structure which is loaded with a ferromagnetic thin film and a dielectric material characterized by a permittivity which is a function of an external electric field.

The thin film and dielectric material are biased to desired quiescent values of permeability and permittivity by current and voltage amplifiers respectively coupled thereto. The current and voltage amplifiers are adapted to respond to a common input signal by generating like percentage changes in the film permeability and the permittivity of the field responsive material.

Since the product of the film permeability with the dielectric permittivity is variable, while their quotient is constrained to remain constant, the instant arrangement comprises a constant characteristic impedance for any selected wave delaying time interval.

It is to be understood that the above-described arrangement is only illustrative of the application of the principles of the present invention. Numerous other arrangements may be devised by those skilled in the art with-

out departing from the spirit and scope of the present invention. For example, the strip line 10 illustrated in the FIG. 1 embodiment may be replaced by any well known microwave propagation structure, such as a waveguide or coaxial cable.

What is claimed is:

In combination, means for propagating electromagnetic wave energy along a defined path in a reference direction, means interposed in said path for coupling to wave energy propagated along said path, said coupling means including an elongated ferromagnetic thin film element and an elongated dielectric member each having a main longitudinal axis disposed parallel to said reference direction, said element and said member being characterized by a composite permeability and a permittivity which respectively vary with applied magnetic and electric fields, said composite permeability characteristic including real and imaginary components, means for biasing said member to a value in a range of electric field values that correspond to a linear segment of the permittivity characteristic of said member, means for biasing said element in the vicinity of ferromagnetic resonance to a value in a range of magnetic field values that correspond to a linear segment of the real permeability characteristic of said element, the imaginary component of said permeability being relatively small in said range of magnetic field values, and means connected to said biasing means for varying in a controlled way the electric and magnetic fields supplied thereby.

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