July 29, 1969 DINH-TUAN NGO 3,458,837

FILTER ELEMENT USING FERROMAGNETIC MATERIAL LOADING

Filed Dec. 22, 1966

FIG. 1

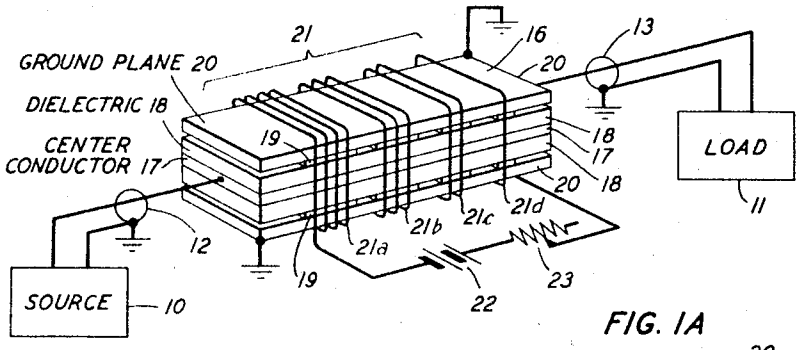


FIG. 1A

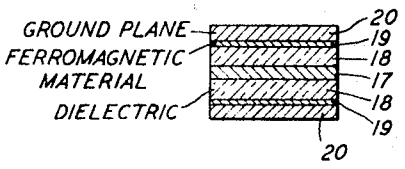


FIG. 2

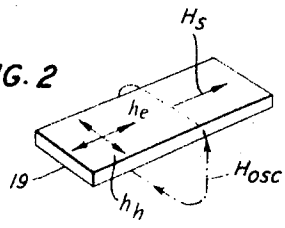


FIG. 3

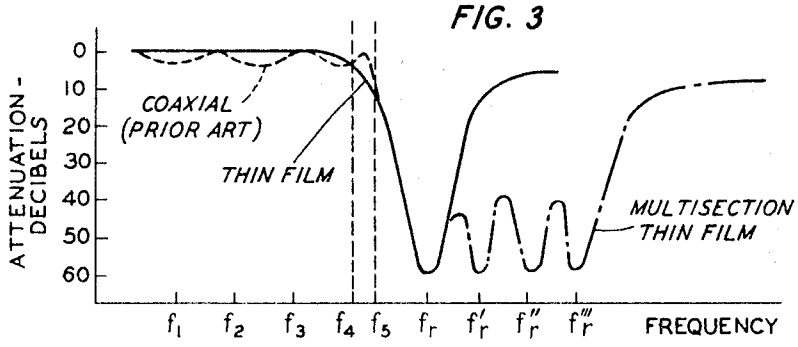
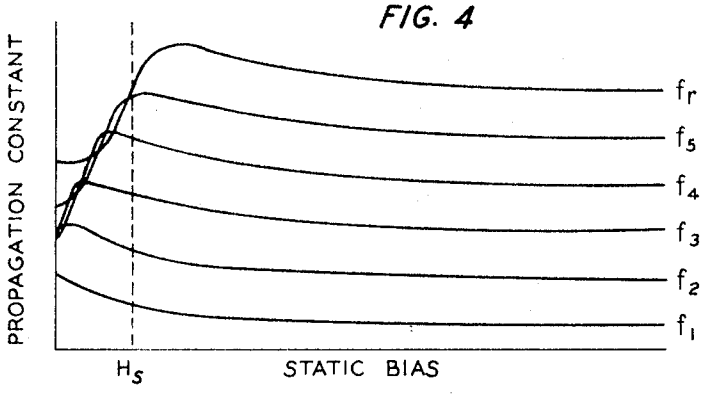


FIG. 4



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FILTER ELEMENT USING FERROMAGNETIC MATERIAL LOADING

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U.S. Cl. 333—73 12 Claims

ABSTRACT OF THE DISCLOSURE

A transmission line includes an element magnetically biased near ferromagnetic resonance to give the line a low pass filter characteristic with essentially flat response in the filter pass band. The magnetic bias is electrically controlled, and plural filter sections in tandem are biased by a multilevel magnetic field with a single electrical control.

BACKGROUND OF THE INVENTION

Field of the invention

This invention relates to an electric signal filter employing biased magnetic means to fix the filter pass band and cutoff characteristics.

Description of prior art

In prior art filters employing lumped circuit constants or employing, in the ultra high frequency range, a conductor shaped at specific different points to act as specific lumped impedance elements, it is known that the pass band attenuation-versus-frequency characteristic includes a ripple. Such ripple represents variations in attenuation of two or three decibels in some cases. Ripple of that magnitude is generally tolerable because it is substantially within the attenuation range considered to characterize the pass band of the filter. However, in some digital systems a cyclic attenuation variation such as the aforementioned ripple produces signal echoes which interfere with the pulse-type information representation employed in the system.

It is, therefore, one object of the invention to reduce ripple in the pass band of a filter attenuation-versus-frequency characteristic.

Furthermore, prior art filters, particularly those employed in higher frequency ranges, are not readily tunable. It is usually necessary to construct a substitute filter in order to shift the cutoff frequency.

It is, therefore, another object of the invention to facilitate the shifting of cutoff frequency in a filter element.

Statement of invention

The aforementioned objects of the invention are realized in an illustrative embodiment in which a ferromagnetic material is arranged adjacent to a conductor of a transmission circuit and is magnetically biased to a level corresponding to ferromagnetic resonance at a predetermined frequency to give the circuit a filter-type attenuation-versus-frequency characteristic that is essentially flat in the filter pass band.

It is one feature of the invention that electrical control is employed for the application of the magnetic bias to make the filter cutoff point electrically tunable.

It is another featuer that plural filter sections are advantageously combined in series and controlled by an electrically driven multilevel bias field.

The drawing

The various features, objects and advantages of the invention may be more completely understood from a consideration of the following detailed description in conjunction with the appended claims and the attached drawing in which:

FIG. 1 is a schematic diagram of a transmission circuit including the invention;

FIG. 1A is a cross-sectional view of a part of FIG. 1;

FIG. 2 is a diagram of a part of FIG. 1 indicating one set of various magnetic orientations therein; and

FIGS. 3 and 4 are diagrams illustrating electrical and magnetic characteristics to facilitate an understanding of the invention.

Detailed description

In FIG. 1 a multifrequency signal source **10** produces a signal including frequency components within a predetermined band. Source **10** is coupled to a load **11** by means of coaxial cables **12** and **13** and an interposed two-conductor transmission circuit **16** which is adapted to operate as a low-pass filter. The transmission circuit **16** is illustrated in the form of a strip transmission line with a center conductor **17** and having symmetrically arranged on either side thereof under each section of a bias coil **21** a pair of dielectric material portions **18**, a pair of ferromagnetic material portions **19**, and a pair of ground conductor portions **20**. FIG. 1A shows a cross section of the mentioned symmetrical arrangement, as found under any section of coil **21**, and taken perpendicular to the propagation direction in conductor **17**. However, in FIG. 1 only the ferromagnetic material portions **19** under coil section **21***a* are indicated by reference character.

Each dielectric portion **18** is advantageously a low loss type of glass slab with Permalloy thin films, for portions **19**, deposited on the surface thereof facing the respective ground plane conductors **20**. Of course, the film can be deposited on a conductor, or different dielectrics can be employed. As is known in the art, such films generally comprise an alloy of metals such as nickel and iron. One such alloy includes approximately 81 percent nickel and 19 percent iron. The magnetic thin film portions **19**, one of which is shown in FIG. 2 with the same orientation as in FIG. 1, are anisotropic thin films. As shown in FIG. 2 each film has the easy magnetization axis thereof in the plane of the film and oriented in the direction of signal propagation through the transmission circuit **16** from the input cable **12** to the output cable **13** as can be seen by comparing FIGS. 1 and 2 of the drawing. The easy axis in FIG. 2 is indicated by an arrow h_e, and the film exhibits bistable remanent magnetic flux conditions of opposite polarity in the direction of that arrow. An arrow h_h in FIG. 2 indicates the corresponding orientation of the hard axis of the film and is in the plane of the film and orthogonal to the direction of propagation in circuit **16**. The arrow H_s in FIG. 2 indicates the orientation of a static magnetic bias which is applied to each symmetrical pair of the film portions **19** by its associated section of coil **21** in FIG. 1.

With hard and easy axes oriented as shown in FIG. 2, the lowest cutoff frequency of the filter depends upon the anisotropy field H_k of a particular film. For example, using present films the cutoff frequency can be taken down to about 600 megahertz for a film with H_k of about 4 oersteds. It has also been found that with hard and easy axis orientations interchanged the theoretical lowest cutoff frequency is zero, but for any given cutoff frequency an additional bias of about $2H_k$ is necessary for the last-mentioned orientation as compared to that shown in FIG. 2.

Coil **21** is energized by a battery **22** which supplies current thereto through a rheostat **23** for adjusting the current level in the coil **21** in order to change the magnetic bias and thereby tune the filter for different cutoff fre-

quencies as will be subsequently discussed in greater detail. Thus, the magnetic film portions **19** are subjected to a magnetic bias which is oriented longitudinally along the direction of propagation of the multifrequency signal from source **10**. The transmission circuit **16** is essentially a two-conductor transmission circuit since both of the ground plane portions **20** are connected to ground. Accordingly, such circuit favors the TEM mode of signal transmission. In such mode the magnetic component of the oscillating signal from source **10** is, at any point along circuit **16**, in a plane which is perpendicular to the direction of propagation. A magnetic field through the film portions **19** is provided by such magnetic component as indicated by the arrow H_{osc} in FIG. 2. Both of the film portions **19** of a pair in FIG. 1 have magnetic orientations as discussed in connection with FIG. 2, and the oscillating magnetic field H_{osc} links both films of each pair in the circuit **16**.

Although a strip line is shown in FIG. 1, the invention is also applicable to coaxial transmission circuits wherein, for example, the magnetic thin film is interposed between the dielectric material and the inner surface of the outer conductor of the coaxial circuit.

Coil **21** is shown in plural sections **21***a* through **21***d* for a reason to be subsequently discussed, but initially the operation of circuit **16** parts enclosed by only the coil section **21***a* are considered. FIG. 3 includes a solid-line attenuation-versus-frequency characteristic for the part of transmission circuit **16** enclosed by coil section **21***a*. In order to produce such characteristic, battery **22** is caused to supply sufficient current to the coil **21** to bias the film portions **19** under coil section **21***a* to ferromagnetic resonance corresponding to a frequency f_r in the multifrequency signal from source **10**. The bias field produced within coil section **21***a* produces in the film portions **19** therein a substantially uniform bias level corresponding to a ferromagnetic resonant state for the frequency f_r. Uniformity of bias has reference to any film cross section, and it is not necessary that each cross section along circuit **16** have the same bias level. Under these conditions the circuit **16** functions as a low pass filter with a cutoff frequency f_4, below the frequency f_r. In the present illustration the cutoff frequency is, for convenience, defined as the increased attenuation point at which transmission is down three decibels. At the frequency f_4 transmission in the circuit **16** is approximately three decibels down from the level prevailing throughout the remainder of the pass band of interest, which includes the uniformly spaced frequency components f_1 through f_4 in the multifrequency signal from source **10**.

It can be seen in FIG. 3 that the attenuation characteristic for a thin film loaded circuit is essentially uniform in the band including the frequencies f_1 through f_4. Such response results from the presence of a static bias, generated by coil **21**, corresponding to resonance at the frequency f_r. A dashed curve in FIG. 3 is superimposed upon the solid line curve to illustrate a typical attenuation-versus-frequency characteristic for the mentioned prior art coaxial filter which is designed to have essentially the same pass band and cutoff frequency as the transmission circuit **16** of FIG. 1. However, the coaxial filter characteristic in FIG. 3 includes a cyclic ripple having a magnitude of two to three decibels with respect to the flat transmission illustrated for the circuit **16** of FIG. 1. Such ripple is objectionable because it can have the effect of generating echoes in certain transmission circuits as hereinbefore noted.

A single filter section of the type hereinbefore described has at frequencies above the resonant frequency f_r thereof a substantially flat response similar to that in the mentioned low pass band. However, above the frequency f_r the attenuation is greater than below f_r because the filter impedance is different and is not matched wilth the characteristic impedance of cables **12** and **13** whereas it is advantageously matched in the pass band. Greater insertion loss occurs above f_r, but it is not nearly as much as occurs near f_r. Similarly, if filter impedance is advantageously matched a low standing wave ratio characterizes the filter below the cutoff frequency, but unmatched impedance and high standing wave ratio appear above that frequency.

In order to realize a broader stop band above the desired cutoff frequency, plural filter sections in electrical tandem are employed; and this is the full format shown in FIG. 1. FIG. 3 includes a dash-dot curve representing the attenuation-versus-frequency characteristic of a multisection transmission line filter of the film-loaded type hereinbefore described.

The pairs of magnetic thin film portions **19** of FIG. 1 are separated into discrete segments with individual bias coil **21** sections coupled respectively thereto. Alternatively, however, the film may include similar sections in a single film segment which is then subjected to a corresponding multilevel magnetic bias field. The coil **21** includes the sections **21***a*, **21***b*, **21***c*, and **21***d* which are connected in series with one another and with the rheostat **23** across the terminals of the battery **22**. Each coil section has a different number of turns for biasing its associated film portions **19** for ferromagnetic resonance at different frequencies f_r', and f_r'', and f_r'''. Thus, if section **21***d* biases its films to resonance at f_r, the sections **21***c*, **21***b*, and **21***a*, with increasing numbers of turns, bias their respective film pairs to resonance at the higher frequencies f_r', f_r'', and f_r''', respectively.

It is known in the art that thin film can be used to load two-conductor circuits for producing a constant phase variable attenuator. However, such an attenuator is usually operated near resonance in a single-frequency application. Consequently, moderate changes in bias produce substantial attenuation changes and substantial phase changes. The latter changes must be compensated to get the mentioned constant phase result. No phase compensation is required for a filter section as shown in FIG. 1 because the pass band of interest is apart from the resonant point of the films in a frequency sense. In that pass band impedance is substantially constant, and there is no extraordinary phase shift beyond that normally found in a strip transmission line of the same make-up but lacking film loading.

In considering the construction of the transmission circuit filter of the type illustrated in FIG. 1, the designer must select a center conductor **17** with dimensions which are suitable to the signal frequency band of interest as is known for such conductors in strip transmission lines. A similar selection is made for the ground plane portions **20**. The latter portions are illustrated for convenience as having the same width as the central conductor **17**, but it is to be understood that in many applications it is advantageous for the ground plane conductors to be significantly wider than the center conductor, as is known in the art. A convenient dielectric material and thickness are also selected by the designer; and, for example, glass plates with Permalloy film deposited on one side thereof are advantageously employed. The width of the magnetic film portions **19** is advantageously selected to be the same as the width of the center conductor **17**.

The film thickness for portions **19** must be less than the skin depth of the highest frequency in the desired pass band in order to excite a uniform ferromagnetic resonant mode, as hereinbefore described, throughout a cross section of the film. However, the film should be thin enough so that the magnetization vectors rotate essentially in a plane parallel to the film plane. Where the cutoff frequency of the filter is to be tunable, it is necessary that the film thickness be selected to be less than skin depth of the highest anticipated cutoff frequency in the tuning range. It has been found that if a substantially uniform ferromagnetic resonant mode is not produced throughout the film portions **19**, the circuit will have substantially higher insertion loss in the pass band. It also causes a marked reduction in the sharpness of the attenuation-versus-frequency

characteristic at the cutoff frequency. It has been further found that the use of films of less than 500 A. requires film lengths that are inconvenient in order to get enough ferromagnetic material volume to produce the desired attenuation levels outside the pass band.

The remaining parameters of the transmission circuit **16** for a single filter section, e.g., that under coil section **21***a*, are film length and bias field strength. The film length can be readily computed by techniques which are known in the art. Thus, for example, the designer determines the permeability of the particular film as a function of static bias field by employing the Landau-Lifshitz equation which is known in the art. In this connection, see page 6 in subsection 1A of doctoral thesis of D. Ngo entitled "A Strip Line With Variable Magnetic Film Discontinuity," dated 1962, and on file in the library of Iowa State University of Science and Technology in Ames, Iowa. Using that permeability the designer then solves the Maxwell equations for a strip line having a ground plane with adjacent Permalloy films in order to get the propagation constant of the line. Such constant is expressed in terms of attenuation per unit of length. Knowing the total attenuation which is desired at the cutoff frequency, the length of the film can be determined from the propagation constant.

At this point it remains only to determine the appropriate static magnetic bias field which must be applied, i.e., to determine at what frequency the magnetic film portions **19** should be capable of resonating in order to produce the aforementioned desired attenution at the cutoff frequency and with essentially flat response in the pass band. It has been found that this latter information can be determined by plotting a family of propagation constant-versus-static bias characteristics for different frequencies of interest, as shown in FIG. 4. The characteristic for each frequency in FIG. 4 approaches the horizontal axis asymptotically as static bias is increased beyond the bias corresponding to ferromagnetic resonance for such frequency. The characteristics are shown, at least in part, in FIG. 4 for the frequencies f_1 through f_5 and f_r. With this family of characteristics, the designer then finds the characteristic for his desired cutoff frequency and looks in the static bias range above resonance for that characteristic for a common bias level at which the characteristics for uniformly spaced frequencies across the pass band of interest are also uniformly spaced at the common static bias level. This point is designated as the bias H_s in FIG. 4 and corresponds approximately to the ferromagnetic resonant bias at a signal frequency f_r which was previously not specifically identified. When the film portions **19** of a filter section are uniformly subjected to the static bias level H_s, indicated in FIG. 4, they cause the transmission circuit **16** to produce the solid-line attenuation-versus-frequency characteristic illustrated in FIG. 3.

In one embodiment that was actually constructed and operated for a single section filter with a theoretical pass band down to zero frequency, the principal parameters were as follows:

Cutoff frequency—nominal value in tuning range	1 gigahertz.
Film thickness	1.0×10^{-10} meter.
Film width	0.318 centimeter.
Film length	2.5 centimeters.
Dielectric type	Corning Microscope slide glass.
Dielectric thickness	1.513×10^{-4} meter.
Conductor **17**—width	3/32 inch.
Conductor **17**—thickness	0.004 inch.

Such filter had a characteristic impedance in the pass band of about 10 ohms. A 50-ohm filter can be made by using film of four times the indicated length and dielectric of five times the indicated thickness. The latter type filter can, of course, be coupled to widely-used 50-ohm cable without impedance transformation which often has a band limiting effect.

For a transmission circuit with plural filter sections to produce a characteristic such as the dash-dot characteristic in FIG. 3, the previously outlined design procedures are followed for each section except that the resonant frequency and static bias level for each additional section after the first are not selected from FIG. 4. The resonant frequency and corresponding bias for each successive section are selected to produce in the stop band above f_r a desired minimum average attenuation with respect to the pass band attenuation. The extent of the stop band of high attenuation and the magnitude of ripple in that part of the characteristic are functions of the number of sections employed and the spread among resonant frequencies as will be readily appreciated by those skilled in the art.

Although the invention has been described in connection with a particular embodiment thereof, it is to be understood that additional embodiments and modifications which will be obvious to those skilled in the art are included within the spirit and scope of the invention.

What is claimed is:

1. In a filter comprising input means for receiving a multifrequency signal and an output circuit, the improvement comprising

a transmission line coupling components of said signal below a predetermined frequency from said input means to said output circuit, said line having a first conductor, a ground plane conductor, and dielectric material between said first conductor and the ground plane conductor,

an electrically conductive ferromagnetic member between one of said conductors and an adjacent portion of said dielectric material, and

means applying to said member a magnetic field perpendicular to the magnetic component of said signal and of sufficient magnitude to bias said member to a level corresponding to a ferromagnetic resonance condition at a second frequency above said predetermined frequency to provide a substantially uniform impedance to a predetermined hand of frequencies of said signal below said predetermined frequency.

2. The filter in accordance with claim **1** in which said ferromagnetic member is a magnetic thin film having anisotropic magnetic characteristics with hard and easy magnetization axes in the plane of said film and orthogonal to one another, one of said axes being parallel to the direction of signal propagation in said line.

3. The filter in accordance with claim **1** in which said ferromagnetic member is a magnetic thin film having anisotropic magnetic characteristics with an easy magnetization axis in the plane of said film and orthogonal to the direction of signal propagation in said line and a hard magnetization axis in the plane of said film and parallel to said direction of propagation.

4. The filter in accordance with claim **3** in which said ferromagnetic thin film is adjacent to said ground plane conductor.

5. The filter in accordance with claim **1** in which said ferromagnetic member is biased substantially uniformly throughout any given cross section thereof.

6. The filter in accordance with claim **1** in which said transmission line is a strip transmission line having ground plane conductors and dielectric material portions symmetrically disposed on either side of said first conductor, and

said ferromagnetic member includes portions between each of said ground conductors and its corresponding dielectric material portion.

7. The filter in accordance with claim **1** in which said ferromagnetic member separates its adjacent conductor and dielectric material by a distance corresponding to the thickness of such member, said thickness being less than the skin depth of said predetermined frequency component of said signal.

8. The filter in accordance with claim 7 in which said ferromagnetic member has a length proportioned with respect to the propagation constant of said transmission line to produce a predetermined attenuation level, with respect to signal transmission level in said predetermined band, at said predetermined frequency.

9. The filter in accordance with claim 1 in which propagation constant-versus-magnetic bias field characteristics for predetermined frequencies of said signal are, at a bias level corresponding to said second frequency, substantially uniformly spaced at uniformly separated frequencies in said predetermined band below said predetermined frequency.

10. The filter in accordance with claim 1 in which said magnetic field applying means comprise a coil wrapped around a portion of said transmission line including said ferromagnetic member, and means applying different selectable current levels to said coil.

11. The filter in accordance with claim 1 in which said means coupling said transmission line between said input means and said output circuit consists of direct wire connections.

12. In a filter comprising input means for receiving a multifrequency signal and an output circuit, the improvement comprising

a transmission line coupling components of said signal below a predetermined frequency from said input means to said output circuit, said line having a first conductor, a ground plane conductor, and dielectric material between said first conductor and the ground plane conductor,

a ferromagnetic member between one of said conductors and an adjacent portion of said dielectric material, said member including a plurality of sections in successive tandem parts of said transmission line, and

means applying to said member a magnetic field perpendicular to the magnetic component of said signal and of sufficient magnitude to bias said member to a level corresponding to a ferromagnetic resonance condition at a second frequency above said predetermined frequency to provide a substantially uniform impedance to a predetermined band of frequencies of said signal below said predetermined frequency, said field applying means including a corresponding plurality of field applying sections associated with respective ones of said transmission line tandem parts for biasing said ferromagnetic member sections therein to different levels each corresponding to a ferromagnetic resonance condition at a different frequency above said predetermined frequency.

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U.S. Cl. X.R.

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