# United States Patent

**Vasile**

[15] **3,670,271**

[45] **June 13, 1972**


[54] **TWO PORT MAGNETOELASTIC DELAY LINE**


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[73] Assignee: **Hazeltine Corporation**



[22] Filed: **Sept. 18, 1970**

[21] Appl. No.: **73,287**

[52] **U.S. Cl.** .......... **333/30,** 330/4.5, 330/5, 333/24.1

[51] **Int. Cl.** .......... **H03h 7/30**

[58] **Field of Search** .......... 333/24.1, 24.2, 29, 30, 30 M, 333/31; 330/4.6, 4.5, 5


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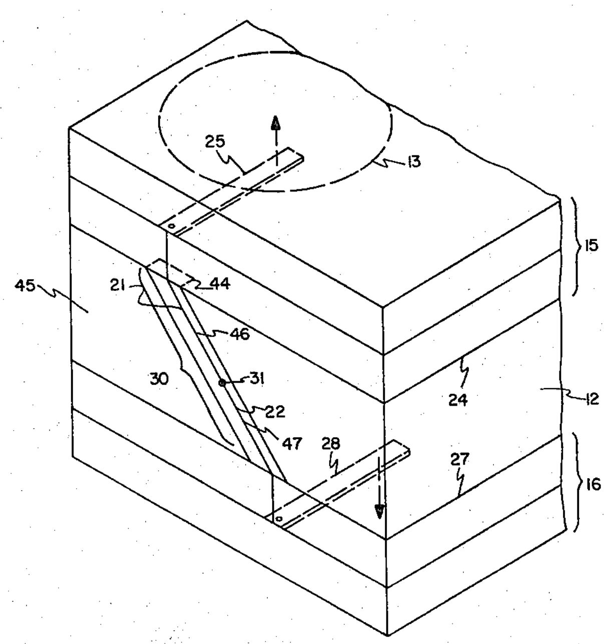
*Attorney*—Edward A. Onders


[57] **ABSTRACT**


A two port magnetoelastic delay line in which the coupling elements of an electromagnetic coupling structure are arranged in a colinear configuration at the end-face of a piece of single crystal yttrium iron garnet (YIG) to which electromagnetic energy is coupled. The sample of YIG is located in an axially varying magnetic bias field whose lines of magnitude include concentric circles of constant magnitude which increase in value radially from a point near the center of the end-face of the YIG, and the coupling devices are positioned so that each device crosses the same circle of magnitude only once, and so that the coupling devices together traverse the maximum number of concentric circles of magnitude of the bias field at the end-face. Alternate embodiments are also considered.


**14 Claims, 11 Drawing Figures**



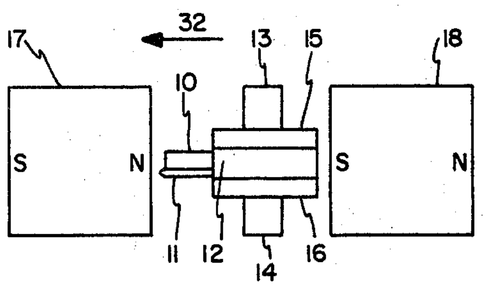



FIG. 1a

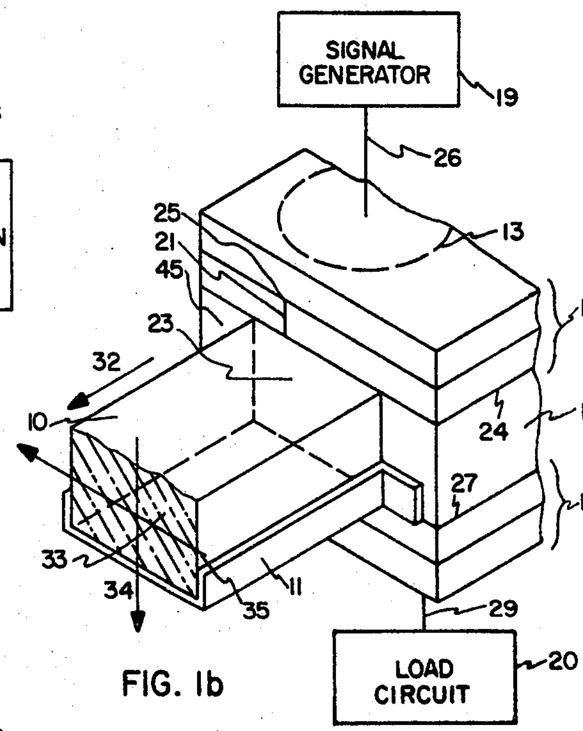



FIG. 1b

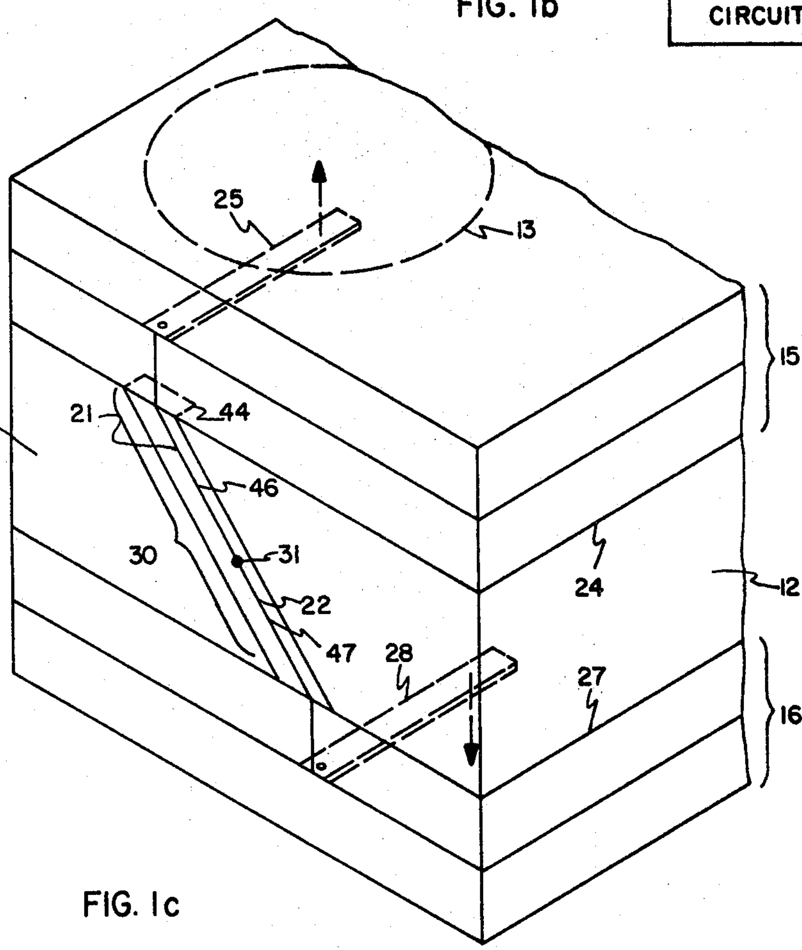



FIG. 1c

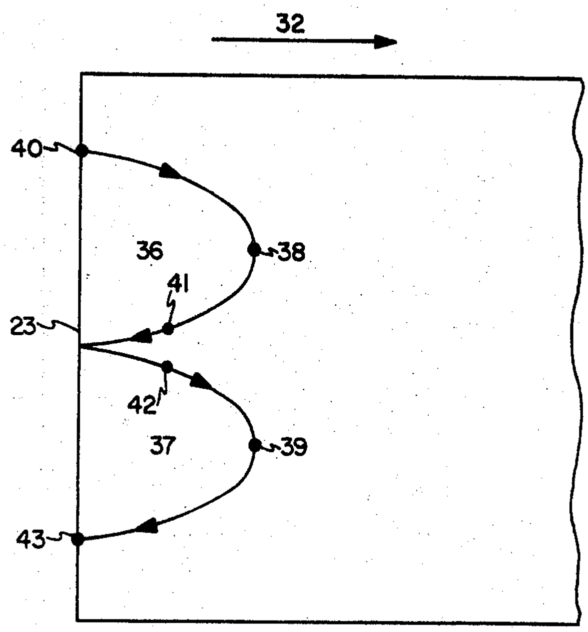



FIG. 2

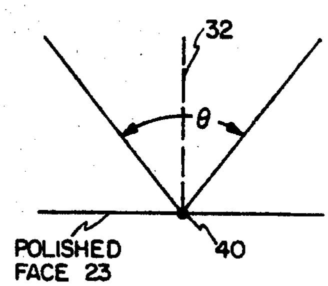



FIG. 4

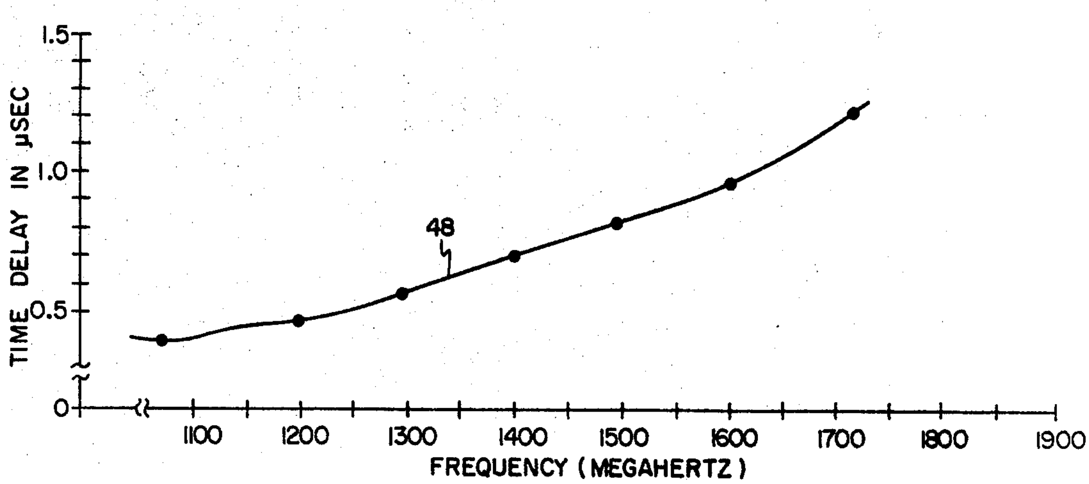



FIG. 3a

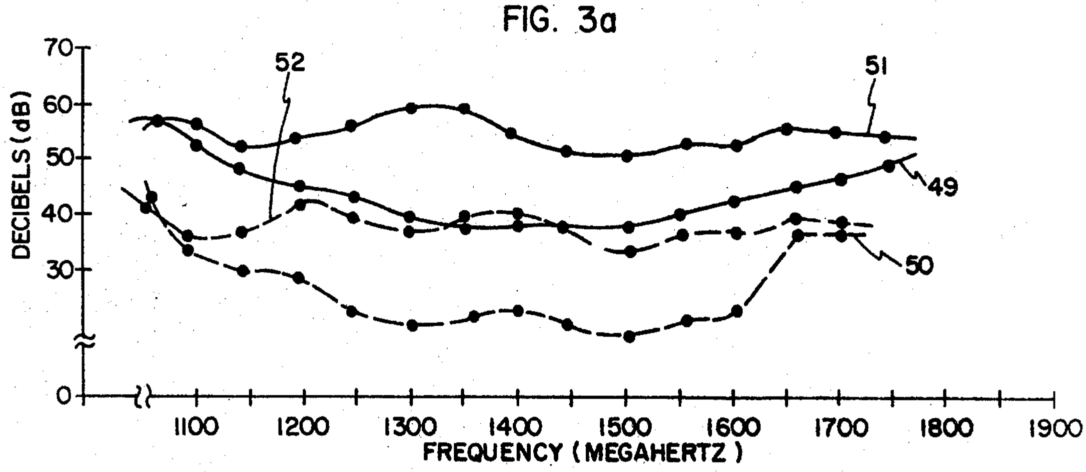



FIG. 3b

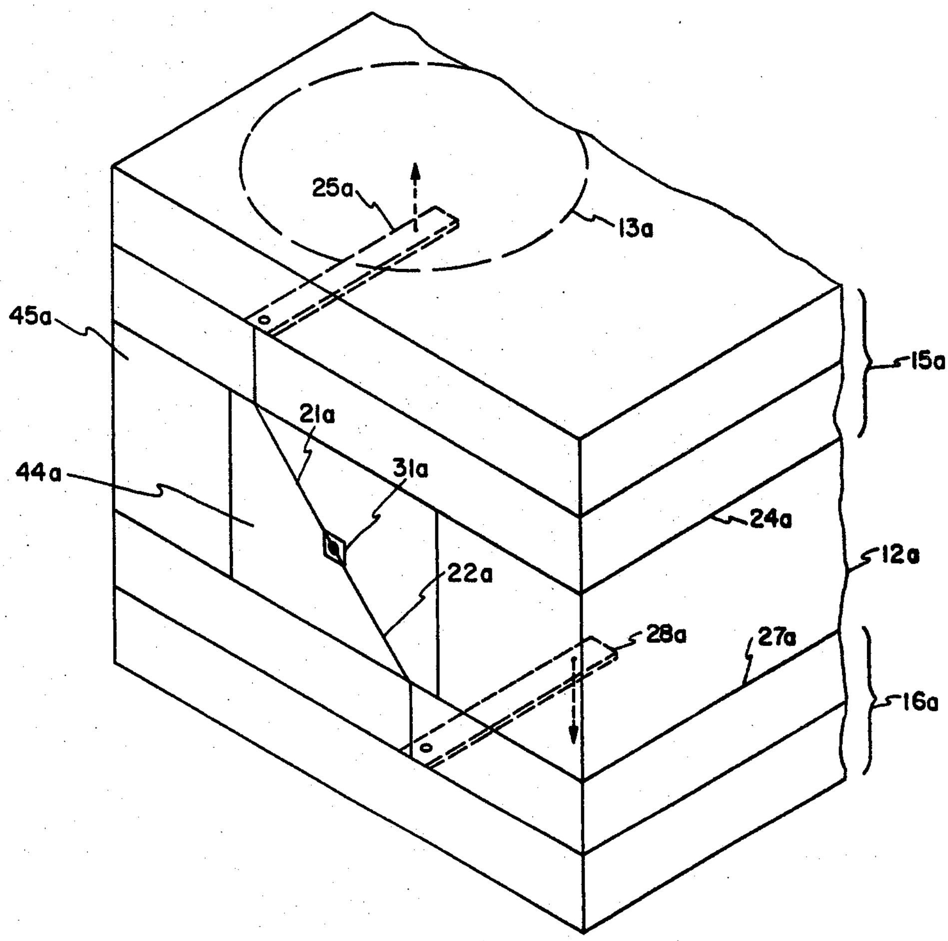



FIG. 5

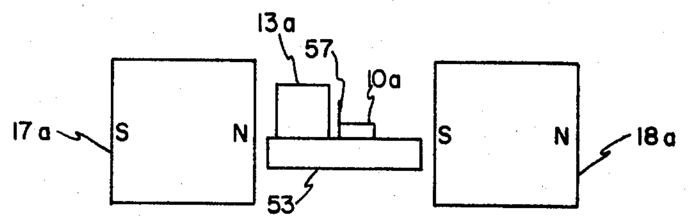



FIG. 6a

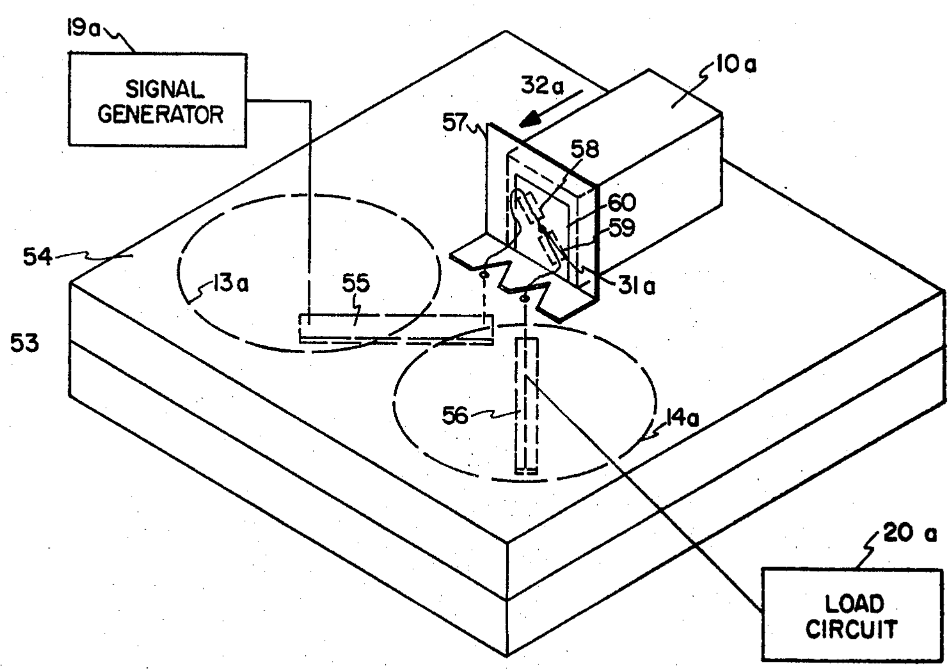



FIG. 6b

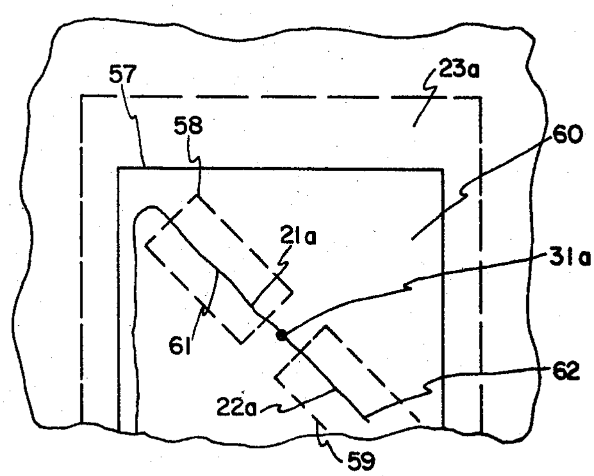



FIG. 6c

# TWO PORT MAGNETOELASTIC DELAY LINE

## CROSS REFERENCE TO RELATED APPLICATIONS

This application relates to two port magnetoelastic delay lines such as those described in the related copending application of C. F. Vasile, Ser. No. 762,067, filed on Sept. 24, 1968 entitled "Two Port Magnetoelastic Delay Line".

## BACKGROUND OF THE INVENTION

The present invention relates to delay lines, and in particular to two port magnetoelastic delay lines in which electromagnetic energy is coupled to and from magnetic insulator material by two separate coupling elements.

The above-referenced copending application of Carmine F. Vasile disclosed a two port magnetoelastic delay line in which the input and output coupling elements are located on a common face of magnetoelastic material but separated from each other. The advantages of that device over prior art delay lines is clearly pointed out in the copending application.

In the device disclosed in the copending application, the coupling elements, typically thin conductors, of the input and output couplers are positioned across the face of the magnetoelastic material, such as yttrium iron garnet (YIG), parallel to each other. The present application discloses a two port magnetoelastic delay line in which the coupling elements are oriented in a manner which improves the delay line performance characteristics; in particular, increases bandwidth, reduces signal amplitude and phase distortion, and minimizes alignment and reproducibility problems.

## SUMMARY OF THE INVENTION

Objects of the present invention are therefore to provide an improved two port magnetoelastic delay line which utilizes a new and improved coupling structure element configuration to yield the broadest band performance without sacrificing signal insertion loss and bandwidth performance characteristics, and provides improved performance with respect to prior devices.

In accordance with the present invention there is provided a two port magnetoelastic delay line comprising a sample of magnetic insulator material having a polished face, means for subjecting the magnetic insulator to a spatially varying bias field whose magnitude increases along a longitudinal axis from the polished face into the magnetic insulator material for causing the propagating waves to decrease as they propagate away from the polished face, and whose magnitude also increases radially from the interior of the magnetic insulator material to the exterior of the material within a cross section of the magnetic insulator material. The invention further comprises a first shielded electromagnetic coupling means including a first conductor having a portion of its length contiguous to the polished face of the magnetic insulator material for coupling electromagnetic energy to the magnetic insulator material as a result of high frequency current flow in the first conductor. The portion of the first conductor contiguous to the polished face is oriented so that the magnetic bias field traversed by the described portion increases continuously along the length of that portion. The invention also comprises a second shielded electromagnetic coupling means including a second conductor separated and shielded from the first conductor, and having a portion of its length contiguous to the polished face of the magnetic insulator material for coupling electromagnetic energy from the magnetic insulator material to produce a signal in said second conductor representative of the high frequency signal in said first conductor delayed by a predetermined amount. The portion of the second conductor contiguous to the polished face is oriented so that the magnetic field traversed by the described portion increases continuously along that portion. The second conductor is oriented with respect to said first conductor to insure that undelayed leakage is not coupled directly from the first conductor through the magnetic insulator material to the second conductor in an amount greater than the delayed energy coupled to the second conductor.



For a better understanding of the present invention, together with other and further objects thereof, reference is had to the following description, taken in connection with the accompanying drawings, while its scope will be pointed out in the appended claims.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. *1a*, *1b* and *1c* illustrate a two port magnetoelastic delay line constructed in accordance with the present invention;

FIG. 2 is a representation of an idealized wave propagation in a YIG bar;

FIGS. *3a* and *3b* are a graphical illustration of the performance of a FIG. 1 delay line actually constructed and tested;

FIG. 4 illustrates the radiation characteristics of a wave launched in a YIG bar;

FIGS. 5 and *6a*, *6b* and *6c* are illustrations of alternate embodiments of two port delay lines constructed in accordance with the present invention.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

FIGS. *1a* through *1c* illustrate a two port magnetoelastic delay line constructed in accordance with the present invention. A side view of the delay line approximately actual size is shown in FIG. *1a*, which illustrates a sample of magnetic insulator material **10** positioned in non-metallic channel **11** which is secured to the side of a block of conductive material **12**. Connectors **13** and **14** and stripline sections **15** and **16** couple signals to and from the delay line. Magnetic insulator **10** is positioned between permanent magnets **17** and **18** in order to subject the magnetic insulator material to a magnetic bias field.

FIG. *1b* is an expanded isometric view of a section of the delay line illustrated in FIG. *1a* in which connectors **13** and **14**, permanent magnets **17** and **18**, a portion of magnetic insulator material **10** and stripline sections **15** and **16** have been removed, and in which schematic representations of a signal generator **19** and load circuit **20** have been included.

FIG. *1c* is a further expanded view of FIG. *1b* in which magnetic insulator material **10** and non-metallic channel **11** have been removed to more clearly illustrate a coupling device including thin conductors **21** and **22**.

As stated, the delay line includes a sample of magnetic insulator material **10**. Yttrium iron garnet (YIG) is the preferred type of magnetic insulator because of its low loss characteristics. The YIG material **10** may be in any shape or form, but usually is constructed in the form of a slab, a bar, or cylindrical rod. The type of bias field required, which is described below, however, is easier to achieve in the bar configuration illustrated in FIG. 1, or in a cylindrical rod configuration.

The type of wave propagation required to produce a delay line in accordance with the present invention has only been observed up to the present time in single crystal samples of YIG, and therefore these samples are preferred. The best results have been achieved with a (100) oriented YIG bar, i.e., a single crystal YIG bar which has the longitudinal axis parallel to the crystallographic axis.

The YIG material must have a surface area capable of reflecting elastic waves. In the FIG. 1 embodiment, face **23** of the YIG sample **10** which is contiguous with conductive material **12** is polished so that it will reflect elastic waves.

The delay line also includes input means for receiving a high frequency signal, having a range of predetermined frequency components, which is to be delayed. Included in this means is a first transmission line means such as stripline section **15** having a first grounded conductor **24** and a first ungrounded conductor **25**. Stripline **15** is coupled to signal generator **19** via connector **13** and transmission line **26**.

The delay line further includes a utilization load means for translating a high frequency signal representative of the supplied high frequency signal delayed by a predetermined amount. The utilization load means includes a second transmission line illustrated as a portion of stripline 16 having a second grounded conductor **27** and a second ungrounded conductor **28**. The second transmission line is coupled to load circuit **20** via the connector **16** and transmission line **29**. The second grounded conductor is connected to conductive material **12** along the length of the second grounded conductor **27**. The delay line further includes a first shielded coupling means for coupling electromagnetic energy to the magnetic insulator material **10** representative of the high frequency signal. The coupling device includes a shielding member such as block of conductive material **12** having groove **30** extending across the face **23** of the YIG material. Groove **30** has a width which is less than 0.03 times the shortest free space wavelength of the predetermined frequencies of the high frequency signal. First thin conductor **21** is positioned in groove **30** and connected at one end of the groove to first ungrounded conductor **25** of first transmission line **15** and is connected at the center of groove **30** to conductive material **12** at junction **31**. Conductive material **12** is connected to first grounded conductor **24** along its length.

The delay line further includes means **17** and **18** for subjecting the magnetic insulator material **10** to a spatially varying magnetic bias field whose magnitude increases along longitudinal axis **32** from polished face **23** into YIG material **10** in the direction of arrow **32** and increases radially from the interior of YIG material **10** to the exterior of the material within cross section **33** of YIG material **10**. Placing magnetic material such as YIG between the two permanent magnets **17** and **18** will produce a spatially varying magnetic bias field in the YIG material. The field increases away from the polished face toward the center of the material where it will then begin to decrease in the direction of the opposite face. The field also increases radially from the center of the end face **23**, and its lines of magnitude appear as concentric circles on cross section **33** of the YIG bar **10**.

In order to achieve the operation described below, the field must increase along the length of the YIG bar **10** in which the desired wave propagation occurs. However, if the bar is sufficiently long, all the wave propagation of interest will occur before the point where the field begins to decrease. If the bar is not long enough, a piece of polycrystal YIG may be butted up against the face of the YIG opposite polished face **23** in order to cause the magnetic field to increase for a greater distance through the single crystal piece **10**.

For convenience the means for producing the bias field is illustrated as a pair of permanent magnets **17** and **18** having the particular north south pole orientations illustrated. Other appropriate orientation or types of magnets may be used. An electromagnet or any other suitable device may be utilized. The important criteria is that the field to which the YIG **10** is subjected is sufficient to saturate the YIG in order to provide the desired wave propagation.

The delay line further includes a second shielded coupling means for coupling electromagnetic energy from magnetic insulator material **10** for producing an output signal representative of the high frequency signal coupled to first conductor **21** delayed by a predetermined amount. The second shielded coupling means includes the stated shielding member **12** illustrated as a block of conductive material having a groove **30** and second thin conductor **22** positioned along the length of the groove. The second thin conductor is connected at one end to conductive material **12** at the center of groove **30** at junction **31** and at the opposite end to second ungrounded conductor **28** of stripline **16**. The signal developed in second thin conductor **22** which is representative of the signal flow in first thin conductor **21**, delayed by a predetermined amount, is thereby coupled through stripline **16**, connector **14** and transmission line **29** to the load circuit **20**. The current flow developed in second conductor **22** is opposite in direction of the flow of current in first conductor **21**.

The first thin conductor **21** and second thin conductor **22** are positioned substantially co-linear, each extending from the center of polished face **23** in opposite directions along a common axis to the perimeter of the polished face so that the magnetic field traversed by the conductors increases continuously along the length of each of the conductors.

Thin conductors **21** and **22** are shielded from one another against propagation through the air by having their fields confined by the shielding member **12**. Undelayed leakage through the magnetic insulator **10** is minimized by the spacing between the conductors.

## DETAILED DESCRIPTION OF THE OPERATION OF THE PREFERRED EMBODIMENT

As previously described, the YIG material **10** is capable of providing a dispersive delay making it particularly attractive as a component of a compression filter. However, the device may also find application as a non-dispersive delay line, for example, by suitably shaping the bias field. In either case, the signal to be delayed is a high frequency signal in the range of 350 MHz to 10 GHz. Generally speaking, YIG material has been utilized with signal frequencies between 1 and 10 GHz.

The signal to be delayed is coupled from signal generator **19** through connector **13** and center conductor of stripline **15** to first thin conductor **21**. Polished face **23** of YIG material **10** is adjacent to and preferably in direct contact with first conductor **21** and therefore current flowing in first conductor **21** causes electromagnetic energy to be coupled to YIG material **10** in the region of polished face **23** thereby launching a medium-*k* wave in the YIG material **10**.

FIG. **2** illustrates the type and direction of wave propagation that may occur in YIG material **10** and is an idealized configuration in which the axis of YIG bar **10** is coaxial with the magnetic field indicated by arrow **32**. It has been empirically determined that the best operation is obtained by tilting the axis of the YIG with respect to the magnetic field axis. YIG **10** is positioned in the magnetic field at an angle which minimizes the insertion loss and the spurious signals which occur at twice the desired delay. The proper orientation must be empirically determined. Among other things, it depends on the strength and shape of the magnetic fields and the length of the YIG bar. It has been found that the proper orientation will even vary with different YIG samples. Generally, with the YIG properly aligned for a minimum insertion loss and minimum spurious signals, the YIG axis is no more than 15° off the magnetic field axis.

The magnetic bias field strength is varied by adjustments in the spacing between permanent magnet **18** and YIG material **10**. The delay line is then tuned by feeding a pulsed carrier signal into the input port of the delay line and then adjusting the bias field strength with the axis of YIG **10** orientated parallel to the bias field direction. The bias field strength is adjusted until a transmitted signal is produced which is delayed by a predetermined amount. This predetermined value of time delay is an empirically determined parameter and is dependent upon the frequency and dimensions of YIG **10**. Once the magnetic bias field strength is adjusted, fine tuning is accomplished by slight adjustments in the magnetic bias field strength and orientation of YIG **10** about a first axis **34** and a second axis **35**, both of which are mutually perpendicular and parallel to the polished end face **23**. By slight adjustments in orientation, insertion loss and spurious signals are minimized.

The effect that tilting the YIG bar with respect to the magnetic field axis has on the idealized waveform of FIG. **2** is not fully understood. It is believed that the propagation path segments **36** and **37** are not symmetrical and accordingly, branch points **38** and **39** do not occur at the same distance from polished face **23**. Even though the shape of the propagation path in the preferred case is not exactly as illustrated, FIG. **2** will be explained in order to facilitate an understanding of the type of waves propagated and some understanding of the direction of propagation. The terms medium-*k* and high-*k*, exchange spin-wave, which are used below, have been used in an article by Carmine F. Vasile and Richard LaRosa entitled

"Guided Wave Propagation In Gyromagnetic Media As Applied To The Theory Of Exchange Spin-Wave Excitation", appearing in the Journal of Applied Physics, Vol. 39, No. 3, Pages 1863–1873, dated Feb. 15, 1968.

As indicated in FIG. 2 the medium-k wave propagates away from launch point **40**, located on polished face **23**, and which corresponds to the position of first conductor **21**. As the wave propagates away from polished face **23** in the direction indicated by the arrowheads the wavelength decreases due to the increasing bias field until it reaches branch point **38** where the medium-*k* wave converts to a high-*k* exchange spin-wave. The exchange spin-wave has a component of propagation back in the direction of polished face **23**. It should be noted, however, that the ray paths illustrated in FIG. **2** are a simplification of the actual paths, which are strongly dependent upon the bias field variation and geometry.

The branch point **38** must occur within the region of increasing magnetic bias field. For a relatively long YIG bar, for example, a bar which is 0.3 inch long, the branch point will occur before the middle of the bar and therefore within the region of increasing bias field. If the length of the bar is too short, the branch point might fall outside the region of increasing bias field. However, the magnetic bias field can be shaped to cause the region of increasing magnetic bias field to occupy a greater portion of the length of the bar. For example, a length of polycrystal YIG placed adjacent to single crystal bar **10** at the end of the bar opposite polished face **23** causes a larger portion of single crystal YIG bar **10** to have an increasing bias field.

The wavelength of the high-*k* exchange spin-wave propagating towards polished face **23** continues to decrease until it reaches point **41** where the wavelength approximates the wavelength of an elastic wave. At this point the high-*k* exchange spin-wave converts to an elastic wave of corresponding wavelength. The elastic wave continues to propagate in the direction of polished face **23** where it is reflected and propagates away from polished face **23** to point **42** where it reconverts to a high-*k* exchange spin-wave. The exchange spin-wave continues to propagate away from the polished face until it reaches branch point **39** where it reconverts to a medium-*k* wave. The medium-*k* wave propagates towards polished face **23** where it induces a current flow at reception point **43** in second conductor **22** which is related to the original current flow in first conductor **21** delayed by a predetermined amount. The delayed signal is then coupled through strip line **16** and connector **14** to load circuit **20** for further signal processing.

One of the major difficulties associated with producing a practical YIG delay line has been in achieving an output which can be separated from the input and whose level is greater than the undelayed leakage. Undelayed leakage refers to the energy which couples directly from input conductor **21** to output conductor **22** either through the air or through the YIG without undergoing any delay. In the present invention, shielding against direct coupling through the air is achieved by shielding input and output conductors **21** and **22** respectively, as illustrated. The input and output couplers each consist of a block of conductive material having a groove **30** whose width is less than 0.03 times the shortest free space wavelength of the signal to be delayed, traversed by first and second conductors **21** and **22** respectively which are substantially colinear and connected to the block of conductive material at the center of groove **30** at junction **31**. In the region of the groove **30** the conductors **21** and **22** are separated from the block of conductive material **12** by a dielectric section of material **44** placed in the groove **30** between the conductors **21** and **22** and the walls of block of conductive material **12**. First and second conductors **21** and **22** whose widths are less than 0.010 inch are preferably placed inside groove **30** flush with front face **45** of block of conductive material **12** so as to make direct contact with YIG material **10** which is butted against front face **45**. The width of the groove is preferably less than one-eighth of an inch.

Conductive material **12** confines the electromagnetic fields produced by current flow in each of conductors **21** and **22**. Placing the conductors in the groove confines the relevant fields primarily to the widths of the groove thereby preventing any substantial coupling between conductors **21** and **22** through the air. Groove **30** also serves to shield the YIG material from much of the return currents. Most of the return currents will flow in the sidewalls of the groove and the field associated with them will not couple to the YIG, thereby reducing a potential source of spurious coupling.

Direct undelayed coupling through the YIG bar **10** is avoided by orienting output coupler conductor **22** with respect to input coupler **21** to insure that any undelayed energy coupled directly through the YIG from first conductor **21** to second conductor **22** is substantially less than the delayed energy coupled to second conductor **22**. According to the teaching of the prior art, exciting the polished face **23** by passing current through input conductor **21** produces an effect across polished face **23** which is analogous to launching the dominant waveguide mode whose field extends across the entire polished face **23**. Applicant has discovered that, in fact, the waves launched by current flow in first conductor **21** interfere in such a manner as to cause the plane wave energy to be confined within a relatively narrow angle $\theta$, illustrated in FIG. **4**, centered around the magnetic bias field, which changes direction at each point on conductor **40**. Outside the angle $\theta$ the energy decays exponentially. Accordingly, there is no substantial radiation transverse to the axis of the magnetic field, i.e., along polished face **23**, unlike the situation where the dominant waveguide mode only is excited.

The amount of separation between conductors required to prevent substantial undelayed coupling through the YIG is related to the length of the conductors. Points **46** and **47** midway along the length of first conductor **21** and second conductor **22** respectively must be separated by at least one-third the length L of the longer conductor in order to achieve the desired isolation. With this minimum spacing as the lower limit, the optimum spacing must be empirically determined. Decreasing the gap at junction **31** between first conductor **21** and second conductor **22** increases the bandwidth. However, undelayed coupling also increases as the distance between the conductors is decreased. Undelayed coupling suppression is therefore sacrificed to provide maximum bandwidth performance.

First and second conductors **21** and **22** are positioned at end face **23** of YIG **10** in a colinear configuration as illustrated in FIG. **1*c*** to prevent undesired performance characteristics, for example, amplitude distortion and reduced bandwidth performance. Applicant has discovered through study of the internal magnetic bias field of a ferromagnetic cylinder that the lines of constant magnitude of the magnetic bias field exist on end face **23** as concentric circles which increase in value radially from a point near the center of end face **23** to the perimeter of the end face. For a YIG bar of square geometry, the lines of constant magnitude are not concentric circles but are distorted closed concentric curves that approximate circles near the YIG bar axis. The bias field, however, will still have its smallest magnitude at the center of the end face. Positioning each of the conductors **21** and **22** as illustrated in FIG. **1*c*** so that each extends from approximately the center of polished face **23** to its perimeter causes each conductor to cross a line of constant bias field magnitude only once. If either of the conductors **21** and **22** were to cross any of these lines of constant bias field magnitude more than once, redundant coupling paths between the input and output couplers are created which affect the performance of the delay line in several ways, namely, reduce the bandwidth, increase signal insertion loss and generally distort the delayed signal. However, in the present configuration the magnitude of the magnetic bias field increases in value along the lengths of each of conductors **21** and **22** from the center of end face **23** at junction **31** to the perimeter of the end face of YIG **10**. This arrangement prevents redundant transmission paths through the

YIG material between input and output couplers 21 and 22 respectively and eliminates the above-mentioned undesirable performance characteristics which otherwise degrade performance of the delay line.

The maximum bandwidth performance is achieved by positioning the first and second conductors in a colinear configuration along a common axis across end face 23 of the YIG 10 so that the conductors traverse the maximum number of lines of constant bias field magnitude which exist across the end face of the YIG. Conductors 21 and 22 will traverse the maximum range of the bias field magnitude when their combined length in the colinear configuration across the end face of a sample of YIG form the line of maximum possible length for the particular geometric shape of the end face. For example, in the present invention, maximum bandwidth performance is obtained by positioning conductors 21 and 22 in diagonal groove 30 extending across rectangular end face 23 of YIG sample 10. For a circular end face, maximum bandwidth performance would be obtained when the conductors were positioned so as to extend across the diameter of the end face.

FIG. 3 is a graphical illustration of the results obtained with a delay line constructed in accordance with FIG. 1. The relevant parameters are listed below:

| | |
|---|---|
| (100) Single Crystal YIG bar | .125 inch x .135 inch x 3.00 inches |
| Wire size of first conductor 21 | .003 inch |
| Wire size of second conductor 22 | .003 inch |
| Width of groove 30 | .012 inch |
| Distance between conductors 21 and 22 at junction 31 | .005 inch |
| Distance between points 46 and 47 of conductors 21 and 22 | .097 inch |
| Permanent magnets 17 and 18 | 3 stacked 1 inch x 1 inch x .4 inch barium ferrite magnets (Indiana General Index V) for each |

Since the combined length of both conductors traversing the YIG is 0.1834 inch, each conductor is approximately 0.092 inch long. Since the gap between conductors 21 and 22 at the center of groove 30 at junction 31 is 0.005 inch, the distance between points 46 and 47 which are midway along the lengths of respective conductors 21 and 22, is approximately 0.097 inch. This distance is substantially greater than one-third the length of the longer conductor, as specified above.

The curve 48 in FIG. 3*a* illustrates the variation in time delay, plotted in microseconds along the ordinate, versus frequency, plotted in megahertz (MHz) along the abscissa. Since the delay varies with frequency as illustrated, this is a dispersive delay line. Since the variation is linear over a wide portion of the spectrum, it would also make a good linear FM pulse compression filter.

The curves 49 and 50 shown in FIG. 3*b* are plots of the untuned and tuned insertion loss respectively plotted in decibels along the ordinate, versus frequency. At almost all the points plotted the insertion loss is substantially less than the attenuation of the undelayed leakage, represented by curves 51 and 52, the untuned leakage and tuned leakage respectively. Therefore an output signal which is greater than the undelayed leakage has been provided. For example, at 1,500 MHz the output signal is approximately 15 db greater than the undelayed leakage, making separation of the output signal from the undelayed leakage very convenient.

The portion of the bandwidth over which the delay variation with respect to frequency is linear should also be noted. The useful bandwidth illustrated in FIG. 3*a* is approximately 500 MHz.

## DESCRIPTION OF THE ALTERNATE EMBODIMENTS OF FIGS. 5 AND 6

FIGS. 5 and 6 illustrate alternate embodiments of a two port magnetoelastic delay line constructed in accordance with the present invention.

FIG. 5 is an alternate construction of FIG. 1*c*. The parts of the delay line not shown in FIG. 5 are the same as the delay line illustrated in FIG. 1*a* and 1*b*. The delay line of FIG. 5 includes the sample of single crystal yttrium iron garnet shown in FIG. 1*a*. The delay line also includes input means for receiving a high frequency signal, having a predetermined range of frequencies, which is to be delayed. The input means includes strip-line section 15*a* having first grounded conductor 24*a* and first ungrounded conductor 25*a*. The delay line also includes second transmission line 16*a* having second grounded conductor 27*a* and second ungrounded conductor 28*a* for translating a high frequency signal representative of the supplied high frequency signal delayed by a predetermined amount. The delay line illustrated in FIG. 5 further includes a block of conductive material 12*a* having substantially flat face 45*a* adjacent and parallel to the polished face of YIG material 10 and having first and second grounded conductors 21*a* and 22*a* arranged substantially colinear on flat face 45*a* and connected to conductive material 12*a*. As stated, face 45*a* of conductive material 12*a* is substantially flat and does not include groove 30 illustrated in FIG. 1*c*.

The FIG. 5 delay line further includes first thin conductor 21*a* positioned along the diagonal of face 45*a*, isolated from the flat face by a layer of dielectric material 44*a* and having a width which is less than 0.010 inch. First conductor 21*a* is coupled at one end to ungrounded conductor 25*a* of first transmission line 15*a* and connected at the other end at the center of flat face 45*a* to the block of conductive material at junction 31*a*, for coupling electromagnetic energy to YIG material 10 as a result of high frequency current flow in the portion of first conductor 21*a* which is coextensive with flat face 45*a*.

The delay line further includes means for subjecting YIG material 10 to a spatially varying d-c magnetic bias field whose magnitude increases along longitudinal axis 32 from polished face 23 into YIG material 10 and increases radially from the interior of YIG sample 10 to the exterior of the YIG within cross-section 33 of YIG material 10, illustrated as a pair of permanent magnets 17 and 18 in FIG. 1. The requirements of the field described with reference to FIGS. 1*a* – 1*c* are identical for the FIG. 5 embodiment.

The delay line illustrated in FIG. 5 further includes second thin conductor 22*a* positioned along the diagonal of flat face 45*a*, isolated from the block of conductive material 12*a* along the flat face by a layer of dielectric material 44*a*, and having a width which is less than 0.010 inch. In FIG. 5, the same dielectric layer 44*a* isolates wires 21*a* and 22*a* from conductive material 12*a* in the region of flat face 45*a*. It will be obvious that this isolation could be provided by two separate pieces of dielectric material individually associated with their respective conductors 21*a* and 22*a*.

First and second conductors 21*a* and 22*a* are positioned adjacent to the flat face 45 and oriented so that the magnetic field traversed by said conductors increases continuously along the length of each of said conductors. First and second thin conductors 21*a* and 22*a* are positioned substantially colinear and extend from the center of end face 45*a* to the perimeter of the end face, in substantially opposite directions along a common axis and are separated by a small gap at their connection to conductive material 12*a* at junction 31*a* so that the conductors traverse the maximum number of bias field magnitude variations across end face 23 of the YIG and provide the maximum bandwidth performance.

Second thin conductor 22*a* is coupled at one end to ungrounded conductor 28*a* of second transmission line 16*a* and coupled at the opposite end to conductive material 12*a* at the center of flat face 45*a* at junction 31*a*, for producing a current flow in second conductor **22a** which flows in the opposite direction of the current flow in first conductor **21a** representative of the high frequency signal coupled to first conductor **21a**, delayed by a predetermined amount.

The operation of the FIG. **5** embodiment is similar to the operation of the FIGS. **1a**, **1b** and **1c** embodiments. The signal to be delayed is coupled to first transmission line **15a** from the signal generator through connector **13a**. Current flow in first conductor **21a** couples energy to the YIG material which propagates in accordance with the propagation paths described by FIG. **2**. The delayed signal is detected by second thin conductor **22a** and accordingly a signal is developed in second conductor **22a** which is representative of the signal flowing in first conductor **21a** delayed by a predetermined amount. The output signal is then coupled from second conductor **22a** to load circuit **20** via strip-line **16a** for further processing.

The FIG. **5** delay line is simpler and easier to construct than the FIG. **1c** delay line. As stated, flat face **45a** does not have a groove such as illustrated at **30** in the FIG. **1c** delay line. It is apparent that the shielding of return or ground currents which groove **30** in FIG. **1c** provides is not provided in the FIG. **5** embodiment; however, the delay line does provide good coupling, and delayed outputs which are substantially greater than the undelayed leakage are readily obtainable. This is due to the fact that the ground currents are dispersed somewhat over the face of ground plane **45a** which is separated by a finite distance from YIG material **10**.

FIG. **6** is an illustration of another embodiment of a two port magnetoelastic delay line constructed in accordance with the present invention.

FIG. **6a** is a side view of a delay line shown approximately actual size. FIG. **6a** illustrates a sample of YIG material **10a** positioned on strip-line section **53**. Strip-line section **53** is actually two separate transmission lines or strip-lines, there being two separate ungrounded conductors positioned between the two outer grounded conductors. However, it is possible to use separate grounded conductors with each of the ungrounded conductors. Signals are coupled to and from the delay line by connectors **13a** and **14a**, which is hidden by connector **13a**, and the separate ungrounded conductors of strip-line section **53**. The magnetic insulator **10a** is positioned between permanent magnets **17a** and **18a** in order to subject the magnetic insulator material to a d-c magnetic bias field.

FIG. **6b** is an expanded isometric view of a section of the FIG. **6a** delay line in which connectors **13a** and **14a**, permanent magnets **17a** and **18a**, and a portion of strip-line **53** have been removed to facilitate understanding of the present invention. The location of connectors **13a** and **14a** are indicated by the dotted circles **13a** and **14a**. In addition block diagram representations of signal generator **19a** and load circuit **20a** have been included in order to indicate the orientation of the delay line in a signal processing system.

FIG. **6a** is a further expanded partial front view of magnetic insulator material **10a** more clearly illustrating the relative sizes and orientations of the electromagnetic couplers.

As stated, the FIG. **6** delay line includes a sample of magnetic insulator material **10a** such as a sample of yttrium iron garnet of the type described in conjunction with descriptions of FIGS. **1** and **5**, including polished face **23a**. The delay line also includes input means for receiving a high frequency signal, having a predetermined range of frequencies, which is to be delayed. The input means includes the strip-line section consisting of first grounded conductor **54** and first ungrounded conductor **55**. The delay line also includes utilization load means including a second transmission line consisting of second grounded conductor **54** and second ungrounded conductor **56** for translating the high frequency signal representative of the supplied high frequency signal, delayed by a predetermined amount.

The delay line further includes a thin layer of conductive material **57**, positioned contiguous to polished face **23a** of YIG material **10a**, and having narrow apertures **58** and **59** arranged substantially colinear, and separated by a portion of the conductive material at the center of polished face **23a** at junction **31a**, and each having a width less than 0.03 times the shortest free space wavelength of said predetermined frequencies and having said first and second grounded conductors connected at the center of end face **23a** to the side of the conductive material opposite YIG material **10a**.

In FIG. **6** it is apparent that grounded conductor **54** is utilized as the grounded conductor for both transmission lines which include ungrounded conductors **55** and **56**, and therefore in the FIG. **6** embodiment the first and second grounded conductors are physically the same conductor, conductor **54**.

The delay line illustrated in FIG. **6** further includes means for subjecting the YIG material to a spatially varying d-c magnetic bias field whose magnitude increases along longitudinal axis **32a** from polished face **23a** into the YIG material and increases radially from the interior of YIG material **10a** to the exterior of the material within cross-section **32a** of YIG **10a**, illustrated as a pair of permanent magnets **17a** and **18a**. The requirements of the bias field are identical to the bias field described with reference to FIGS. **1** and **5**.

The FIG. **6** embodiment further includes a first thin conductor **21a**, positioned adjacent conductive material **57** across aperture **58** transverse to its width so that the magnetic field traversed by first conductor **21a** increases continuously along the length of said first conductor. First conductor **21a** is connected to the layer of conductive material at the center of face **23a** of conductive material **57** at junction **31a**, and shielded from YIG material **10a** by the thin layer of conductive material **57** except for a portion of conductive wire **21a** which traverses aperture **58** transverse to its width. Conductor **21a** has a width which is substantially less than the width of aperture **58** and is coupled at one end to ungrounded conductor **55** of the first transmission line and at the opposite end to the same side of the sheet of conductive material **57** as first grounded conductor **21a** at junction **31a** for coupling electromagnetic energy to the YIG material as the result of high frequency current flow in the portion of the first conductor which traverses aperture **58** while causing substantially all the return currents associated with the current flow in first conductive wire **21a** to be shielded from the YIG material **10a**.

The FIG. **6** embodiment further includes second thin conductor **22a** positioned on conductive material **57** across aperture **59** transverse to its width so that the magnetic field traversed by second conductor **22a** increases continuously along the length of said second conductor. Second conductor **22a** is connected to conductive material **57** at the center of face **23a** of conductive material **57** at junction **31a**, and shielded from YIG material **10a** by the thin layer of conductive material **57** except for a portion of second conductive wire **22a** which traverses aperture **59** transverse to its width. Second thin conductor **22a** has a width which is substantially less than the width of second aperture **59** and is coupled at one end to second ungrounded conductor **56** of the second transmission line and at the opposite end to the same side of the sheet of conductive material **57** as second grounded conductor **22a** at junction **31a**, for producing a current flow in second conductor **22a** representative of the high frequency signal coupled to first conductor **21a**, delayed by a predetermined amount, for causing substantially all the return currents associated with current flow in second conductor **22a** to be shielded from YIG material **10a**.

First and second thin conductors **21a** and **22a** extend from substantially the center of end face **23a** of YIG material **10a**, to the perimeter of said end face, and are separated by a small gap at the point of their connection to the layer of conductive material **57** at junction **31a**, so that said first and second conductors traverse the maximum number of bias field magnitude variations on end face **23a** of YIG material **10a** and provide the maximum bandwidth performance for the delay line. The width of apertures **58** and **59** of the FIG. **6** embodiment is preferably less than one-eighth of an inch, and the width of first and second conductive wires **21a** and **22a** is preferably less than 0.010 inch.

The operation of the FIG. 6 embodiment is similar to the operation of the FIGS. 1 and 5 embodiments. The principal difference is in the nature of the shielded coupling devices illustrated in FIG. 6. Shielded coupling devices of this type are the subject matter of U.S. Pat. No. 3,526,856 granted to Edward F. Heldt, in which this type of coupler is described and the operation fully explained. In brief, the input and output couplers, respectively, consist of thin conductive sheet **57**, having narrow apertures **58** and **59** traversed by conductors **21***a* and **22***a* respectively. In the region of the apertures, the conductors are separated from conductive material **57** by dielectric sheet **60**. Current passing through first conductor **21***a* couples energy to the magnetic insulator material **10***a* and energy coupled from the magnetic insulator material induces a current in second conductor **22***a*, which is representative of the input signal coupled to first conductor **21***a* from signal generator **19***a*, delayed by a predetermined amount. The remainder of the operation of the FIG. 6 embodiment is substantially the same as the FIG. 1 embodiment. The propagation of energy in the YIG is exactly as described in conjunction with the description of FIG. 1. As more fully explained in the above-mentioned U.S. patent of Edward F. Heldt, the width of apertures **58** and **59** should be no greater than 0.03 times the shortest free space wavelength of said predetermined frequencies.

As in the FIG. 1 and FIG. 5 embodiments, first and second conductors **21***a* and **22***a* should be separated by at least one-third the length of the portion of the conductors which traverse apertures **58** and **59** between points **61** and **62**, which are midway along the length of the first and second conductors respectively. Adequate shielding against direct coupling through the air is provided by having a portion of conductive material **57** separating apertures **58** and **59** so that they are in fact two distinct apertures. The FIG. 6 embodiment provides shielding of the ground currents by causing them to flow on the side of conductive member **57** opposite polished face **23***a* of YIG material **10***a*.

Other configurations for apertures **58** and **59** may be utilized, although the illustrated configuration is preferable. As previously stated, a maximum bandwidth performance is achieved when first and second thin conductors **21***a* and **22***a* traverse the maximum number of bias field magnitude variations across end face **23***a* of YIG material **10***a*. Decreasing the length of apertures **58** and **59** results in decreased bandwidth performance, but also results in reduced undelayed leakage. The length of the apertures represent a compromise between the desired bandwidth performance and undelayed leakage suppression.

While there have been described what are at present considered to be the preferred embodiments 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 to cover all such changes and modifications as fall within the true spirit and scope of the invention.

What is claimed is:

1. A two port magnetoelastic delay line comprising:

a sample of single crystal magnetic insulator material having a polished face;

means for subjecting the magnetic insulator to a spatially varying magnetic bias field whose magnitude increases along a longitudinal axis from the polished face into the magnetic insulator material for causing the wavelength of the propagating waves to decrease as they propagate away from the polished face, and whose magnitude also increases radially from the interior of the magnetic insulator material to the exterior of the material within a cross section of the magnetic insulator material;

first shielded electromagnetic coupling means including a first conductor having a portion of its length contiguous to the polished face of the magnetic insulator material for coupling electromagnetic energy to the magnetic insulator material as a result of high frequency flow in said first conductor, said portion of said first conductor oriented with respect to said polished face such that the magnetic field traversed by said conductor increases continuously along the length of said portion of said first conductor; and

a second shielded electromagnetic coupling means including a second conductor separated and shielded from said first conductor, and having a portion of its length contiguous to the polished face of the magnetic insulator material for coupling electromagnetic energy from the magnetic insulator material to produce a signal in said second conductor representative of the high frequency signal in said first conductor delayed by a predetermined amount, said portion of said second conductor oriented with respect to said polished face such that the magnetic field traversed by said portion increases continuously along said portion of said second conductor, said second conductor also oriented with respect to said first conductor to insure that undelayed leakage is not coupled directly from the first conductor through the magnetic insulator material to the second conductor in an amount greater than the delayed energy coupled to the second conductor.

2. A two port magnetoelastic delay line as specified in claim 1 in which said first and second conductors are substantially colinear.

3. A two port magnetoelastic delay line as specified in claim 1 wherein said first and second conductors are substantially colinear, each extending from the center of said polished face and in substantially opposite directions along a common axis to the perimeter of said polished face, whereby said conductors traverse the maximum bias field magnitude variation across the polished face of said magnetic insulator material.

4. A two port magnetoelastic delay line as specified in claim 3 in which the magnetic insulator material is a sample of single crystal yttrium iron garnet (YIG).

5. A two port magnetoelastic delay line comprising:

a sample of single crystal yttrium iron garnet (YIG) having a polished face;

input means for receiving a high frequency signal which is to be delayed;

first shielded coupling means for coupling electromagnetic energy to the YIG material representative of said high frequency signal for launching a magnetostatic wave in said YIG material, including a first conductor responsive to said high frequency signal and having a portion of its length contiguous with the polished face of the YIG material and a shielding member having a surface area substantially larger than the surface area of said portion of the first conductor for confining the electromagnetic fields associated with current flow in said first conductor;

means for subjecting the YIG material to a spatially varying d-c magnetic bias field whose magnitude increases along a longitudinal axis from the polished face into the YIG material for causing the wavelength of said magnetostatic waves to decrease as they propagate away from the polished face and whose magnitude also increases radially from the interior to the exterior of the YIG material along a cross section of the YIG material;

and a second shielded coupling means for coupling electromagnetic energy from said YIG material to produce an output signal representative of the high frequency signal coupled to said first conductor delayed by a predetermined amount, including a second conductor having a portion of its length contiguous to the polished face of the YIG material outside the region of the polished face highly excited by current flow in said first conductor and shielded from said first conductor by a shielding member having a surface area substantially larger than the surface area of said portion of the second conductor for confining the electromagnetic fields associated with current flow in said second conductor, said first and second conductors also being arranged substantially colinear, each extending from substantially the center of the end face in opposite directions along a common axis to the perimeter of said end face, and separated by a small gap at their respective terminations near the center of the end face so as to traverse the maximum bias field magnitude variation across the end face of the YIG material and provide maximum bandwidth performance.

6. A two port magnetoelastic delay line comprising:

a sample of single crystal yttrium iron garnet (YIG) having a polished face;

input means for receiving a high frequency signal having a predetermined range of frequencies, which is to be delayed, said input means including a first transmission line means having a first grounded conductor and a first ungrounded conductor;

utilization load means including a second transmission line having a second grounded conductor and a second ungrounded conductor for translating a high frequency signal representative of the supplied high frequency signal delayed by a predetermined amount;

a block of conductive material having a substantially flat face adjacent and parallel to the polished face of the YIG material and having said first and second grounded conductors arranged substantially colinear on and connected to said conductive material;

means for subjecting the YIG material to a spatially varying d-c magnetic bias field whose magnitude increases along a longitudinal axis from the polished face into the YIG material and increases radially from the interior of the YIG material to the exterior of the material within a cross section of the YIG material;

a first thin conductor positioned adjacent to said flat face and oriented so that the magnetic field traversed by the first conductor increases continuously along the length of said first conductor, isolated from the flat face by a layer of dielectric material, and coupled at one end to the ungrounded conductor of said first transmission line and coupled at the other end to the block of conductive material, for coupling electromagnetic energy to the YIG material as a result of high frequency current flow in the portion of said first conductor coextensive with said flat face;

and a second thin conductor positioned adjacent to said flat face and oriented so that the magnetic field traversed by said second conductor increases continuously along the length of said second conductor, isolated from the block of conductive material along said flat face by a layer of dielectric material, and coupled at one end to the ungrounded conductor of said second transmission line and coupled at the other end to the block of conductive material, for producing a current flow in said second conductor representative of the high frequency signal coupled to said first conductor delayed by a predetermined amount.

7. A two port magnetoelastic delay line as specified in claim 6 wherein said first and second conductors each extend from substantially the center of the end face of said YIG material to the perimeter of said end face and are separated by a small gap at the point of their respective connections to the block of conductive material at the center of said end face so that said conductors traverse the maximum number of bias field magnitude variations across the end face of said YIG material to provide the maximum bandwidth performance.

8. A two port magnetoelastic delay line comprising:

a sample of single crystal yttrium iron garnet (YIG) having a polished face;

input means for receiving a high frequency signal having a predetermined range of frequencies which are to be delayed, said input means including a first transmission line means having a first grounded conductor and a first ungrounded conductor;

utilization load means including a second transmission line having a second grounded conductor and a second ungrounded conductor for translating a high frequency signal representative of the supplied high frequency signal delayed by a predetermined amount;

a block of conductive material having a substantially flat face contiguous with the polished face of the YIG material and having a narrow groove extending across the polished face of the YIG material, said groove having a width which is less than 0.03 times the shortest free-space wavelength of said predetermined frequencies, and having said first and second grounded conductors arranged substantially colinear on and connected to said block of conductive material;

means for subjecting the YIG material to a spatially varying D-C magnetic bias field whose magnitude increases along a longitudinal axis from the polished face into the YIG material and increases radially from the interior of the YIG material to the exterior of the material within a cross section of the YIG material;

a first thin conductor positioned along the length of said groove from the center of said polished face to one end of the groove so that the magnetic field traversed by the first conductor increases continuously along the length of said first conductor, isolated from said conductive material along the length of said groove and connected at the center of the groove to the block of conductive material, for coupling electromagnetic energy to the YIG material as a result of high frequency current flow in the portion of said first conductor coextensive with said groove while causing substantially all the return current associated with the current flow in said first conductor to be shielded from the YIG material;

and a second thin conductor positioned along the length of said groove from the center of said polished face to the other end of said groove so that the magnetic field traversed by said second conductor increases continuously along the length of said second conductor, isolated from said conductive material along the length of the groove, and coupled at the one end of said groove to said second ungrounded conductor and connected at the center of the groove to the block of conductive material, for producing a current flow in said second conductor representative of the high frequency signal coupled to said first conductor delayed by a predetermined amount while causing substantially all the return currents associated with current flow in said second conductor to be shielded from the YIG material.

9. A two port magnetoelastic delay line as specified in claim 8 wherein said first and second conductors each extend from substantially the center of said groove to the perimeter of said end face and are separated by a small gap at the point of their connection to the block of conductive material at the center of said groove so that said conductors traverse the maximum number of bias field magnitude variations on the end face of said YIG material and provide the maximum bandwidth performance.

10. A two port magnetoelastic delay line as specified in claim 9 in which said gap between said first and second conductors is 5 mils, the width of said groove is less than one-eighth of an inch, the width of said first and second conductors is less than 0.010 inch, and in which said first and second conductors are isolated from the block of conductive material along the length of said groove by dielectric material positioned in said groove between said conductors and the block of conductive material.

11. A two port magnetoelastic delay line as specified in claim 10 in which the YIG material is oriented in the magnetic bias field to minimize the insertion loss and to minimize the spurious delay signals.

12. A two port magnetoelastic delay line comprising:

a sample of single crystal yttrium iron garnet (YIG) having a polished face;

input means for receiving a high frequency signal having a predetermined range of frequencies, which is to be delayed, said input means including a first transmission line means having a first grounded conductor and a first ungrounded conductor;

utilization load means including a second transmission line having a second grounded conductor and a second ungrounded conductor for translating a high frequency signal representative of the supplied high frequency signal delayed by a predetermined amount;

a thin layer of conductive material contiguous to the polished face of the YIG material and having first and second narrow apertures separated by a portion of the conductive material at the center of said polished face, each aperture having a width less than 0.03 times the shortest free space wavelength of said predetermined frequencies and having said first and second grounded conductors connected to the side of the conductive material opposite the YIG material at the center of the polished face;

means for subjecting the YIG material to a spatially varying d-c magnetic bias field whose magnitude increases along a longitudinal axis from the polished face into the YIG material and whose magnitude increases radially from the interior of the YIG material to the exterior of the material within a cross section of the YIG material;

a first thin conductor shielded from the YIG material by the thin layer of conductive material except for a portion of the wire which traverses said first aperture transversed to its width, and having a width which is substantially less than the width of said aperture, said wire coupled at one end to the ungrounded conductor of said first transmission line and at the opposite end to the same side of the sheet of conductive material as said first grounded conductor for coupling electromagnetic energy to the YIG material as a result of high frequency current flow in the portion of said conductor which traverses the aperture while causing substantially all the return currents associated with the current flow in said wire to be shielded from the YIG material, said position of said first conductor oriented with respect to said polished face such that



the magnetic field traversed by said conductor increases continuously along the length of said portion of said first conductor;

and a second thin conductor shielded from the YIG material by the thin layer of conductive material except for a portion of the wire which traverses said second aperture transverse to its width, and having a width which is substantially less than the width of said aperture and being positioned substantially colinear with said first thin conductor, said second thin conductor coupled at one end to the ungrounded conductor of said second transmission line and at the opposite end to the same side of the sheet of conductive material as said second grounded conductor for producing a current flow in said second thin conductor representative of the high frequency signal coupled to said first thin conductor delayed by a predetermined amount while causing substantially all the return currents associated with current flow in said second thin conductor to be shielded from the YIG material, said portion of said first conductor oriented with respect to said polished face such that the magnetic field traversed by said conductor increases continuously along the length of said portion of said first conductor.

13. A two port magnetoelastic delay line as specified in claim 12 wherein said first and second conductors each extend from substantially the center of the face of the thin layer of conductive material to the perimeter of said face and are separated by a small gap at the point of their connection to the layer of conductive material at the center of the face of the conductive material so that said conductors traverse the maximum number of bias field magnitude variations on the end face of said YIG material and provide the maximum bandwidth performance.

14. A two port magnetoelastic delay line as specified in claim 13, in which the width of said first and second apertures is less than one-eighth of an inch and the width of said first and second thin conductors is less than 0.010 inches.

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