United States Patent

[11] **3,618,134**

[72] Inventor **Alan B. Smith**
Lincoln, Mass.

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[45] Patented **Nov. 2, 1971**
[73] Assignee **Sperry Rand Corporation**

[54] **HIGH FREQUENCY FERRIMAGNETIC DELAY DEVICE**
7 Claims, 7 Drawing Figs.

[52] **U.S. Cl.** ..... **333/30 M,** 333/31 R
[51] **Int. Cl.** **H03h 7/30,** H03h 9/30
[50] **Field of Search** ..... 333/30, 30 M, 31

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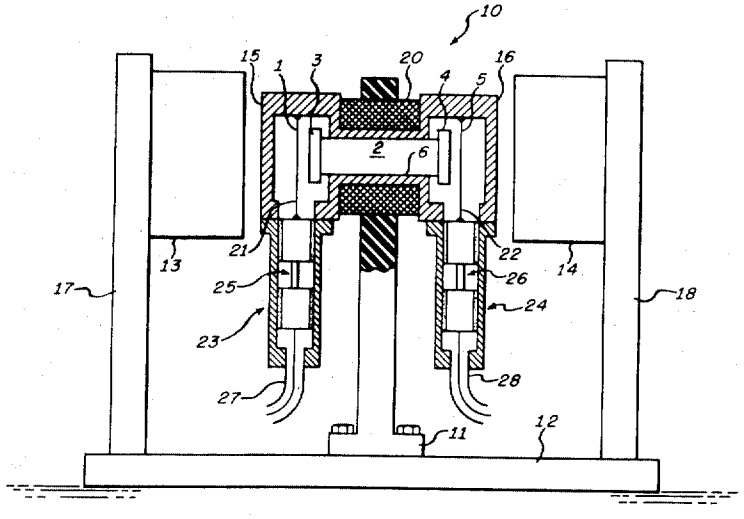
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Primary Examiner—Herman Karl Saalbach
Assistant Examiner—Paul L. Gensler
Attorney—S. C. Yeaton

ABSTRACT: A microwave signal transmission device incorporating an axially magnetized cylindrical yttrium iron garnet rod operates over a broad frequency band as a two port, continuously adjustable, delay device with minimum insertion loss. Broad band operation is achieved by the use of quarter-wave plates of yttrium aluminum garnet crystal cut between principal crystallographic axes and bonded to the input and output ends of the rod.



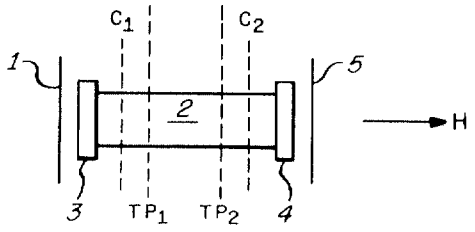


FIG. 1.

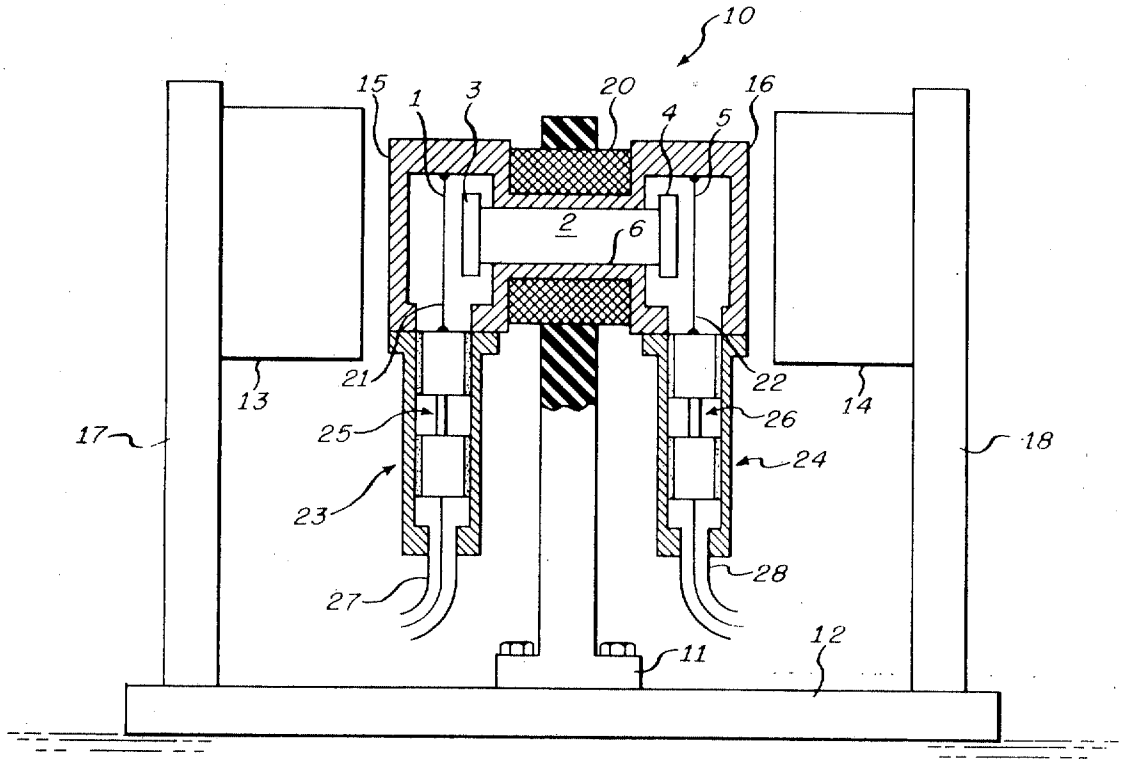


FIG. 2.

INVENTOR
ALAN B. SMITH
BY
ATTORNEY

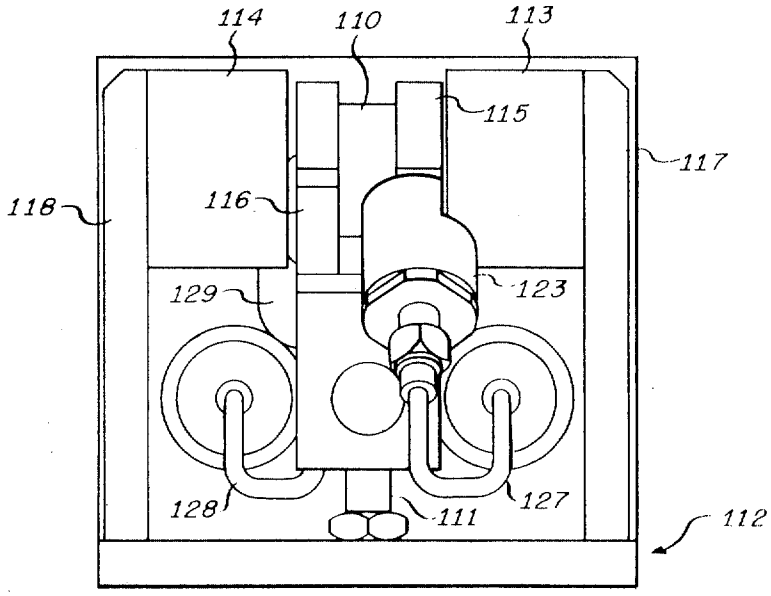


FIG. 3.

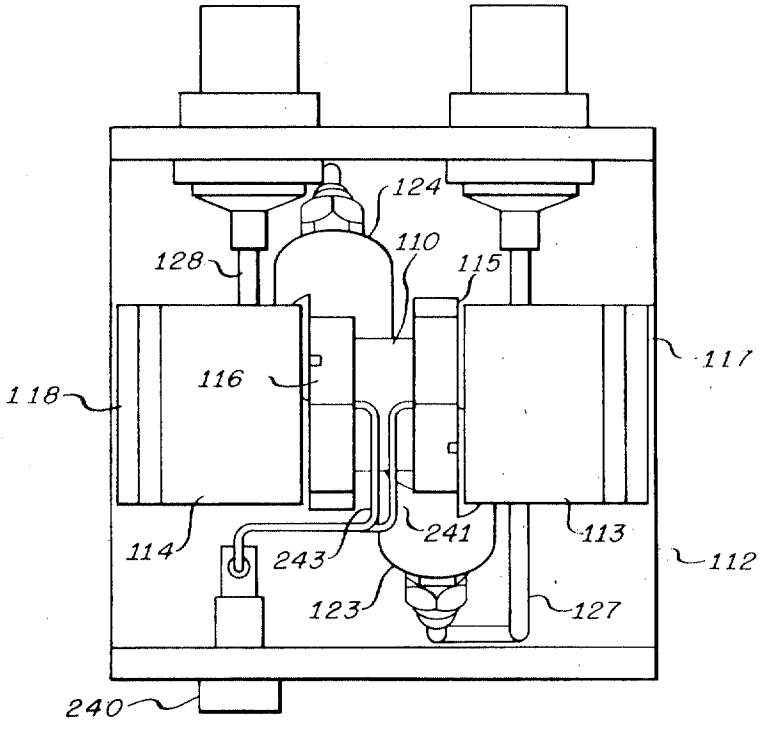


FIG. 4.

INVENTOR
ALAN B. SMITH
BY
ATTORNEY

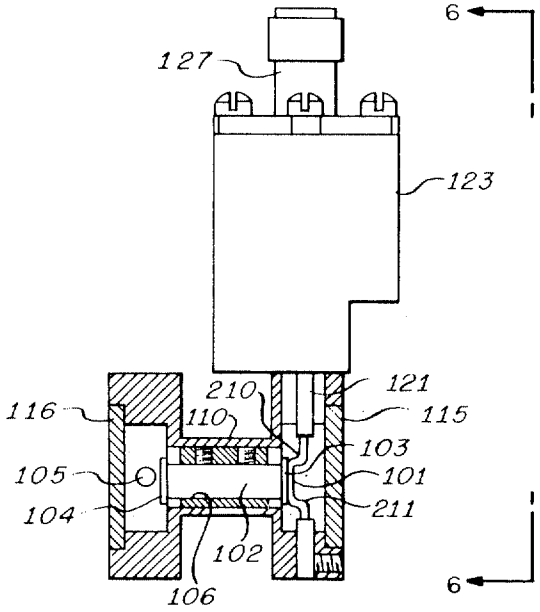


FIG. 5.

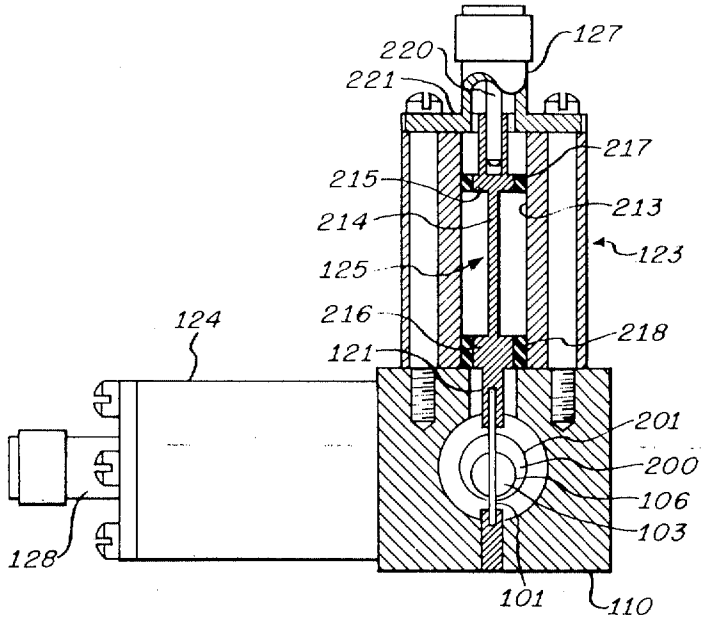


FIG. 6.

INVENTOR
ALAN B. SMITH
BY
ATTORNEY

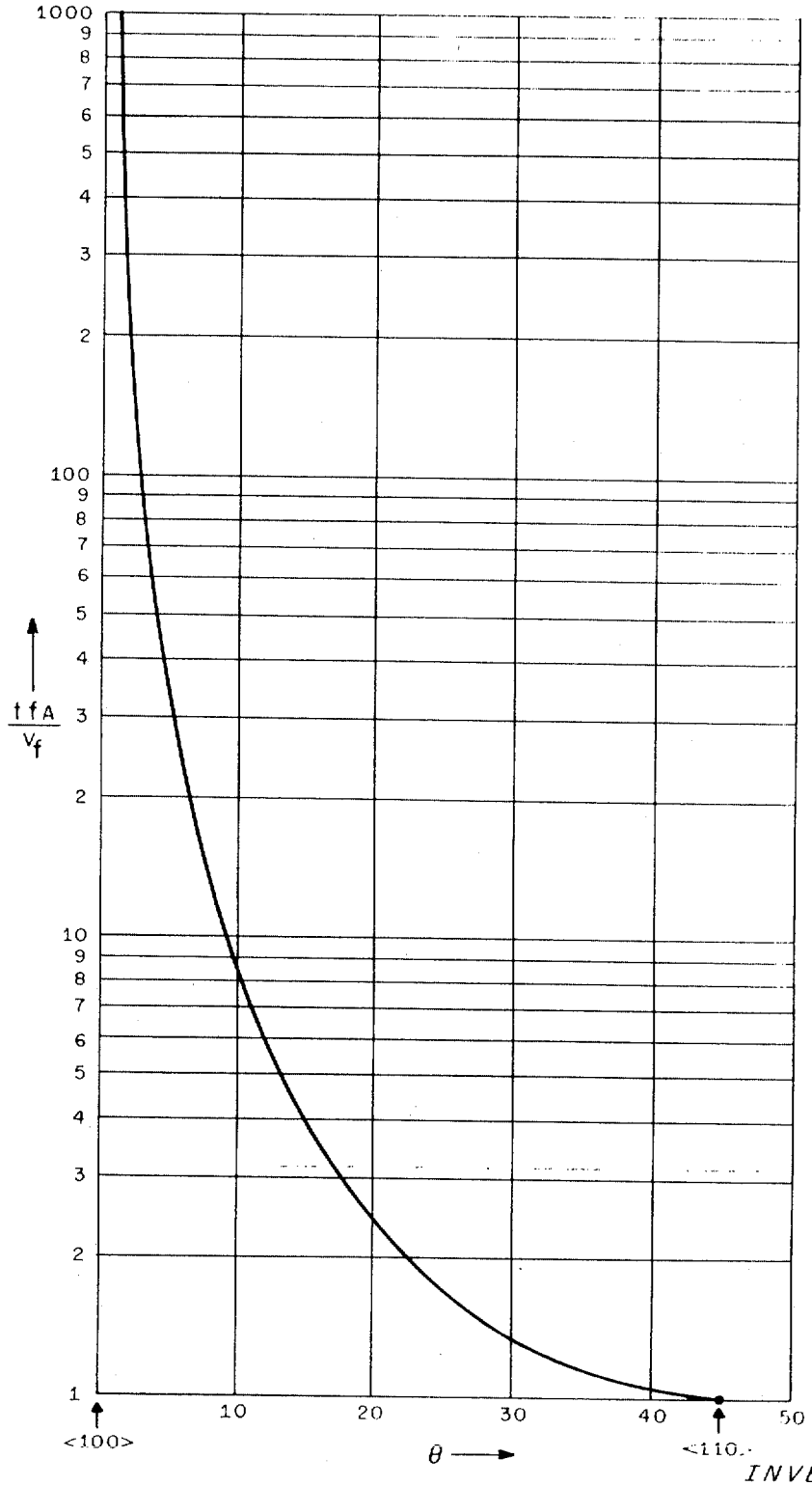


FIG. 7.

INVENTOR
ALAN B. SMITH
BY
ATTORNEY

HIGH FREQUENCY FERRIMAGNETIC DELAY DEVICE

The invention herein described was made in the course of or under a contract or subcontract thereunder with the U.S. Army.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention pertains to means for the selectively controlled, variable delay of microwave signals and more particularly to microwave energy transmission devices permitting continuously variable electrical control of the delay of such high frequency signals over a relatively broad operating bandwidth and with minimum loss.

2. Description of the Prior Art

Fixed delay lines are available in the prior art that are relatively compact and which employ the slow propagation of sound waves in solids. Signals at microwave frequencies coupled to a piezoelectric transducer cause sound waves to propagate through an acoustic transmission medium. These sound waves may be reconverted to microwaves signals at the far end of the transmission medium by reciprocal operation of a similar transducer. Alternatively, these delay lines can be operated as single-port devices instead of in the transmission mode; i.e., the delayed signal is abstracted at the input transducer after reflection at the far end of the transmission medium. However, in either single or two-port operation, the acoustic energy may suffer considerable attenuation in the transducers and in the transmission medium itself. While resonant transducers have been employed, delay lines using them still are characterized by objectionably high insertion loss and have restricted bandwidth as well.

Delay devices which are electrically variable have been constructed of certain magnetic materials wherein the propagation of microwave energy can occur in the form of magnetoelastic or magnetostatic waves. Single crystals of yttrium iron garnet (YIG) have been employed in such delay devices. No separate transducer is required, since the oscillating magnetic field of the microwave signal may be coupled directly to the magnetization of the crystal material. A variable axial magnetic field is used to vary the delay time of the device. The usual manner of operation is again as a single port or reflection device, though the two port or transmission mode of operation has been employed in some applications.

One proposed method of achieving two-port operation of a line having such a magnetically variable delay characteristic is to attach acoustic quarter-wave plates of yttrium aluminum garnet (YAG) to each of the polished ends of the YIG delay medium. One such plate converts the energy into a circularly polarized mode capable of propagating to the far end of the medium, where it is reconverted to a form that may readily be detected there, having suffered only slight attenuation. The function of the quarter-wave plate at the input end of the device is to convert a magnetoelastic wave from positive to negative circular polarization upon reflection from the input end of the delay device. The wave reflected toward the output of the device travels into an identical plate at the output end of the YIG medium, whereupon it is converted to a magnetoelastic wave of positive polarization. Thus, the magnetoelastic signal, formed at one end of the delay device, is detected at its opposite end because of polarization reversal of circularly polarized shear waves. The plates perform their function because of the velocity difference between the two linearly polarized shear waves in the YAG medium. If the plate thickness is such that this relative phase shift is 180°, the circular polarization of the wave leaving the YAG plate has the opposite sense to that it had upon entering the plate.

A serious defect of the proposed YIG device having the two quarter-wave YAG plates lies with constructional difficulties. For instance, calculations have been made of the required thickness for a quarter wave plate designed to supply the desired 180° relative phase change between the two linearly polarized shear waves in the YAG medium. These calculations have lead to the conclusion that the plate thickness would be,

for example, 0.0073 cm. at 1 GHz. for a plate with a 110 crystallographic orientation. The quarter-wave plates must be polished substantially to the state of an optical flat to match and bond to the similarly polished ends of the YIG crystal. Evidently, plates of thicknesses of the order of 0.0073 cm. would be extremely difficult to make and to bond. It has been proven that use of plates thicker than those meeting the above mentioned 180° criterion will cause severe restriction of the bandwidth of the delay device.

The useful bandwidths achieved will then be much less than those obtained using a YIG rod alone in single port operation. Accordingly, prior art electrically alterable delay devices either provide moderate bandwidth but are generally single port devices, or if capable of satisfactory two-port operation, have a seriously restricted operating bandwidth.

SUMMARY OF THE INVENTION

The present invention concerns a broadband microwave signal-delay device of the transmission or dual-port-type incorporating as the delay medium a rod of suitable garnet material and providing continuous adjustability over a wide range of delay values. A rod made of YIG may be employed, dual-port operation being achieved by bonding thin plates of YAG or similar material on each end of the YIG medium. In the invention, YAG plates are employed characterized by having a relatively small difference between the propagation velocities of the fast and slow shear waves within the plates. In preparing the plates, they are cut along a plane lying between the principal crystallographic directions. Complete polarization reversal is then achieved within plates of reasonable thickness such that they can be readily cut and bonded to the YIG medium using established fabrication techniques.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a fragmentary schematic view of certain essential parts of of the invention provided as an aid in understanding a theory of its operation.

FIG. 2 is an elevation view, partially in cross section, of a preferred embodiment of the invention.

FIG. 3 is an elevation view illustrating another embodiment of the invention.

FIG. 4 is a plan view of the apparatus of FIG. 3.

FIG. 5 is a side view, partially in cross section, of a portion of the embodiment of FIGS. 3 and 4.

FIG. 6 is an end view, partly in cross section, of the apparatus of FIG. 5.

FIG. 7 is a universal curve for explaining one theory of the operation of the invention.

FIGS. 1 and 2 present a preferred embodiment of the invention. A magnetoelastic continuously variable delay line is illustrated therein which may be excited, for example, by an input microwave pulse signal traveling from an external source (not shown) along a wire conductor 1 placed in close proximity to a first and of a composite delay structure. The composite structure consists of a single crystal of ferrimagnetic material which may take the cylindrical form of rod 2. Affixed to the respective flat ends of rod 2 are quarter-wave plates 3 and 4. The output of the delay structure is abstracted from it by the wire conductor 5 placed adjacent plate 4 at the output end of the device. Wires 1 and 5 are shown for convenience in FIGS. 1 and 2 as lying in the same plane, i.e., in the plane of the figure, but they may advantageously have other orientations with respect to one another, as will be discussed hereinafter.

When the ferrimagnetic rod 2 with its end plates 3 and 4 is placed within an appropriate axial magnetic field H, the delay between the time of arrival of a microwave pulse on the input conductor wire 1 and its appearance on the output conductor wire 5 varies according to the magnitude of the magnetic field H.

Qualitatively, the operation of the composite delay device is explained as follows: The magnetic field associated with the oscillating microwave currents traveling on conductor wire 1

excites a traveling magnetostatic field within ferrimagnetic rod 2 which travels substantially instantaneously to the left turning point TP1. At TP1, the energy is converted into spin waves which travel only to the left in the figure toward conductor wire 1. These spin waves are reconverted into elastic waves at the so-called crossover point C1. From point C1, the elastic waves continue to travel to the left toward conductor wire 1 and pass into plate 3. Upon reflection at the free surface of plate 3 adjacent conductor wire 1, they pass back through plate 3 and into ferrimagnetic rod 2. Upon reentry into ferrimagnetic rod 2, the elastic waves are found to have the opposite sense of polarization from that which they had upon first entering plate 3. These elastic or acoustic waves continue to travel toward the right hand or output end of the ferrimagnetic rod 2 without spurious interaction with spin waves because of their reversed polarization sense. At the output end of ferrimagnetic rod 2 adjacent conductor wire 5, the plate 4 reconverts the sense of polarization of the acoustic wave back again to that required for interaction with the spin waves. Thus, a reciprocal process involving plate 4, the crossover point C2, and the turning point TP2 results in the propagation of magnetostatic waves toward the right end of the composite delay line structure, where they excite an oscillating magnetic field around conductor wire 5 placed adjacent plate 4. A delayed traveling microwave current thus may be detected by utilization apparatus (not shown) connected to conductor wire 5.

FIG. 2 illustrates in more detail the structure of one form of the invention wherein the composite delay line device consisting of ferrimagnetic rod 2 and plates 3 and 4 is enclosed in a casing 10 of brass or other such metal supported by a bracket 11 of a nonmagnetic material mounted, in turn, upon a base plate 12 of soft magnetic material. Baseplate 12 also affords support for cylindrical permanent magnets 13 and 14 in positions aligned generally with the axis of brass casing 10 and respectively placed at the ends 15 and 16 thereof. Permanent magnet 13 is supported from base 12 by a soft magnetic sheet 17 in close proximity to the end 15 of casing 10. Likewise, permanent magnet 14 is supported above base 12 by a sheet 18 of soft magnetic material in similar close proximity to the end 16 of casing 10. The above described structure thus completes a magnetic flux path for the magnetic field H threading casing 10, the path including, in addition to the airgap region occupied by casing 10, magnet 13, sheet 17, base 12, sheet 18 and magnet 14.

Casing 10 encloses the composite delay structure consisting of ferrimagnetic rod 2 with plates 3 and 4 attached to its respective ends. Ferrimagnetic rod 2 may be round in cross section or of other convenient shape and is held symmetrically within a close-fitting cylindrical portion or longitudinal surface 6 of casing 10 for the purpose of providing isolation between the input and output ends of the composite delay device. Surrounding ferrimagnetic rod 2 and cylindrical portion 6 is a solenoid 20 which may be employed to increase or diminish the magnetic field already threading casing 10 and ferrimagnetic rod 2 because of the presence of permanent magnets 13 and 14. Most of the required magnetic field H is supplied by permanent magnets 13 and 14, while a relatively smaller variable field is usually provided by solenoid 20.

Input signals are coupled through plate 3 into ferrimagnetic rod 2 by an input coaxial transmission line system 23, the extension 1 of whose inner conductor 21 is placed in close proximity with the free face of plate 3 at right angles to the axis of ferrimagnetic rod 2. Similarly, delayed microwave energy may be abstracted from the composite delay device via an output coaxial transmission line system 24, the extension 5 of whose inner conductor 22 passes in close proximity to the free face of plate 4 at the output end of ferrimagnetic rod 2.

The input and output coaxial transmission line system 23 and 24 may include suitable known matching structures 25 and 26, respectively, in view of the reactive impedances of wires 1 and 5. These matching elements may take the form of known microwave coaxial transmission line low pass or bandpass filters. Input and output apparatus (not shown) is respectively coupled to the transmission line structures 23 and 24 via flexible coaxial transmission lines 27 and 28.

The ferrimagnetic rod 2 is preferably fabricated of a single crystal of YIG according to known methods, whereas the end plates 3 and 4 which function as quarter-wave plates may be constructed of YAG or YGaG (yttrium gallium garnet) or of other similar materials. The YIG rod 2 is preferably oriented so that the rod axis coincides with a <100> crystallographic axis of the garnet material.

While garnet materials are discussed herein as desirable materials for the end plates 3 and 4, it should be emphasized that it is primarily the elastic characteristics of the material that are being employed. Therefore, the end plates 3 and 4 may be made of other dielectric materials having appropriate elastic properties and having coefficients of thermal expansion similar to that of YIG. Thus, other materials having a cubic structure may be employed. Noncubic materials could also be used. It is, however, convenient to use YAG or a similar garnet, since such materials are found to be quite compatible with YIG and since, above all, such garnets have similar thermal expansion properties.

End plates 3 and 4 are attached to the respective polished ends of the YIG rod 2 by a method known in the art as optical-contact bonding. This approach is employed because undesired power reflections at the interface between plate 3 and rod 2 and between rod 2 and plate 4 must be very small. Optical-contact bonding results by the actual seizure of optically polished surfaces when any separation between them is reduced well below 1,000 Angstrom units. Surfaces that are highly polished and clean are well known to adhere firmly to each other and to resist large separation forces. The cylindrical surface around the bond may be coated with an epoxy cement to prevent abnormal mechanical shocks from breaking the bond.

As noted above, the prior art proposal has been to construct the plates 3 and 4 in thickness making their fabrication extremely difficult, if not entirely impractical, or to employ relatively thicker plates which cause the maximum useful bandwidth of the device to be severely restricted. In the present invention, this loss in bandwidth is avoided by using quarter-wave plates cut between principal crystallographic directions. Use of quarter-wave plates cut in this manner has afforded greatly increased operating bandwidth for the invention as well as other unexpected and useful results.

The following considerations lead to a general understanding of what can be accomplished according to the method of the present invention in the line of designing quarter-wave plates suitable for use in ferrimagnetic delay lines and yet of a thickness such that fabrication is relatively inexpensive and practical.

The thickness t required for the quarter-wave plates has already been shown in the prior art to be predicted by the equation:

$$t=\frac{1}{4}\frac{V_s}{(V_f-V_s)}\frac{V_f}{f} \qquad (1)$$

as has been indicated above, the thickness t is that thickness which will reverse the polarization of the wave traveling in the quarter-wave plate, one wave component having been retarded by half a wave length more than the other wave component. The propagation velocities are represented by the velocity V_f of the fast shear wave in the plate material and velocity V_s of the slow shear wave, while f is the operating or carrier frequency.

Using classical theorems of acoustic wave propagation in solids, one can again express the difference between the two shear wave velocities by an application of the Christoffel equations for propagation in a {100} plane in terms of the various elastic constants for the material type under consideration. From such an approach, there results an equation

again in terms of the ratio $V_s/(V_f-V_s)$ that appeared in equation 1:

$$\frac{V_f-V_s}{V_s}\cong\frac{1}{4}A\sin^2 2\Theta \qquad (2)$$

Here, A is a composite constant given by:

$$A=\frac{(C_{11}+C_{12})|2C_{44}+C_{12}-C_{11}|}{2C_{44}(C_{11}-C_{44})} \qquad (3)$$

where the C's are the several aforementioned elastic constants for the material of concern. The quantity θ is the angle between the velocity vector in the quarter-wave plate and a <100> crystallographic axis of its material. Combining equations (1) and (2):

$$t=\frac{V_f}{fA\sin^2 2\Theta} \qquad (4)$$

From these relations, the universal curve of FIG. 7 is derived; it shows the quantity ftA/V_f plotted as a function of θ. This universal curve can be used to predict the thickness t of quarter-wave plates of any material with a cubic lattice and enables the discovery of the most desirable value of θ for any selected operating frequency f and for a suitable quarter-wave plate thickness t; i.e., a plate thickness t mechanically suitable for actual generation and use of plates and not so thick as seriously to attenuate the desired signals propagating within the plate. For each plate material, the quantities A and V_s have particular or inherent values.

An example of how the curve of FIG. 7 is used follows for a quarter-wave plate made of YAG. For this material, the constant A is 0.0652; also, $V_f=5.03\times10^5$ cm./sec. Assume that the desired operating or carrier frequency is $f=1.35\times10^9$ cycles per second and assume that $t=0.049$ cm. is a reasonable thickness for the YAG plate. In this case:

$$tfA/V_f=8.58$$

The value 8.58 corresponds on the curve of FIG. 7 to a θ value of 9.9°.

The graph of FIG. 7 in itself shows that useful values of θ would always be less than 45°; i.e., that one would never orient the YAG crystal on a <110> axis as was done in the prior art. Using $A=0.0652$ and $V_f=5.03\times10^5$ cm./sec.:

$$tfA/V_f=1.30\times10^{17}\,tf$$

As long as $tfA/V_f>1$, FIG. 7 shows that θ must be <45°. The condition is satisfied if: $tf>V_f/A$ or, for YAG, if: $tf>7.7\times10^6$.

Because of the inherent properties of the material employed, the minimum carrier frequency at which these microwave delay lines would be employed is 500 mc./sec. or 5×10^8 cycles per second; then tfA/V_f will be less than unity if $t>V_f/fA$ or >0.015 cm. Practical considerations, as aforementioned, make plates as thin as 0.015 cm. **prohibitably costly to make and use. The most desirable value of θ for YAG, for example, is therefore always <45°.**

Other considerations, now to be discussed, place the desirable values of θ for YAG in a range less than 22.5°. As has been observed, plates having a thickness of the order of 0.0073 cm. are extremely difficult to use. While technical improvements in the future may change the achievable useful value of t somewhat, it appears clear at this time that plate thicknesses corresponding to values of θ greater than 22.5° are either not expected to be useful or are not reasonably competitive from a performance or cost view point.

More specifically, the largest reasonably acceptable value of θ would be on the order of 22.5°, since this value is the value that yields a plate thickness twice as thick as that required for the {110} orientation. FIG. 7 indicates that the 2 to 1 relation in thickness always occurs at $\theta=22.5°$ for any cubic material.

The practical lower limit for the parameter θ depends upon the material selected; i.e., for given values of t and f, angle θ is a function of the ratio A/V_f which does depend on the plate material. In YGaG, for instance, it is 3.74 times larger than in YAG.

If YIG is used as the material for the main delay portion of the composite delay device (it is generally preferred,) its characteristics impose a limitation. For example, losses in YIG are known to increase with carrier frequency. At room temperature, they are so high at 6 GHz. that construction of devices above that frequency has not been attempted. Considering the attenuation in YAG and its other characteristics, the thickest plate practical in YAG would probably be about 0.254 cm. Therefore:

$$f=6\times10^9 \text{ cycles/second}$$
$$t=0.254 \text{ cm.}$$
$$A/V_f=0.0130\times10^{15} \text{ sec./cm.}$$

Hence:

$$tfA/V_f=198$$

corresponding to a value of θ on the order of 2°. For a plate constructed of YGaG with the same values of f and t:

$$tfA/V_f=740$$

corresponding to a θ value of approximately 1°. From the foregoing it is seen that a novel feature of the invention lies in the discovery that the angle θ to be selected for quarter-wave plates of any cubic material is preferably below 22.5°. For YAG, a material preferred for use in the quarter wave plates, θ values below 2° are not preferred. For YGaG, a useful alternative material, θ values below 1° are not preferred.

Successful operation of the invention is unexpected from several viewpoints. For example, it has been past practice, in making elastic or magnetoelastic delay devices to avoid any possibility of off-axis propagation in the delay medium. This is because prior art devices have not normally functioned well with off-axis propagation present because the propagation modes are generally neither purely longitudinal nor purely transverse. Also, the direction of energy propagation is not perpendicular to the wave fronts. However, the evidence is that neither of these phenomena has any substantial deleterious effect on the operation of the delay device when the quarter wave plates **3** and **4** are cut in the manner taught in this invention.

While it is not expected that the following explanation will be taken in a limiting sense, it appears that the maximum deviation of the particle motion within the medium of the quarter-wave plates **3** and **4**, when cut in the manner of the invention, from being purely transverse or purely longitudinal is quite small. Thus, only a small fraction of the energy of the pure transverse waves passing from the YIG rod **2** is converted into longitudinal waves in the YAG plate **3**. This effect can provide only negligible loss of the desired signal. Since the acoustic beam is found to be confined by the magnetic field H largely to the center of the YIG rod **2** and hence also to the center of the YAG quarter-wave plates **3** and **4**, deviation of the direction of flow of energy from the wave normal in the YAG plates **3** or **4** is found not to be of consequence.

Employing quarter-wave plates **3** and **4** cut according to the invention, it is found that signal delays, for example, of 3.5 to 8.0 microseconds can readily be achieved at 1.35 GHz. with dual port operation by varying the currents flowing within coil **20** so as to change the magnetic field H applied by magnets **13** and **14** to the composite delay structure including ferrimagnetic rod **2** over a range from 1,200 to 700 Oersteds. With the magnetic field H held constant, the delay time is a function of frequency, enabling the invention also to serve as a pulse compressor in pulse compression communication, radar, or sonar systems or the like. In such applications, a variable magnetic field H is not generally required, and solenoid **20** need not be used or may be employed simply to trim the constant field produced by magnets **13**, **14**.

By employing a casing **10** with a close fitting surface portion **6** fitting snugly around ferrimagnetic rod **2**, direct coupling of energy from input conductor wire **1** to output conductor wire

5 is greatly reduced. Furthermore, by placing input conductor wire 1 at right angles, for example, to output conductor wire 5, isolation between conductors 1, 5 is materially increased and substantially no directly coupled, undelayed signal is found in the output of the delay device. In typical tests, it has been observed that the amplitude of the undelayed input pulse which directly reaches the output port is more than 100 db. below the input pulse amplitude.

A second embodiment of the invention is illustrated in FIGS. 3 to 6 where corresponding reference numerals have been applied to corresponding parts that are also illustrated in FIGS. 1 and 2 though the factor 100 has been added to each such number in FIGS. 3 to 6.

Referring now particularly to FIGS. 3 and 4, there is shown a novel configuration wherein the composite delay device is enclosed in a nonmagnetic casing 110 supported by an adjustable bracket 111 also of nonmagnetic material and affixed to a baseplate 112 of soft magnetic material. Baseplate 112 also affords support for permanent magnets 113 and 114 placed along the axis of casing 110 respectively at the ends 115 and 116 thereof. Permanent magnet 113 is supported above base 112 by magnetic plate 117 in close proximity of the end 115 of casing 110. Similarly, permanent magnet 114 is supported above base 112 by magnetic plate 118 in close proximity to the end 116 of casing 110.

Referring now to FIGS. 3 to 6, casing 110 encloses a composite delay structure consisting of ferrimagnetic rod 102 with plates 103 and 104 cut according to the present invention and attached to the respective ends of rod 102. Ferrimagnetic rod 102 is held within a closely fitting cylindrical portion 106 of casing 110 by means providing adjustability of the rotational position of rod 102 with respect to the magnetic field H and, at the same time, preventing coupling of undelayed energy to the output line 128. The close fitting surface 106 surrounding ferrimagnetic rod 102 may be drilled eccentrically within a brass rod 200 closely fitting, in turn, within a bore 201 within casing 110. Rotation of rod 200 about its axis provides the desired means for adjusting the position of rod 102. Means well known in the mechanical arts may be employed to permit such a rotational adjustment (without translation) whenever desired. Or, once the best position of rod 102 is found, the parts may be fixed together permanently.

The cylindrical portion 106 of casing 110 may be surrounded by a solenoid as at 20 in FIG. 2 which may again be employed to increase or diminish the magnetic field H threading ferrimagnetic rod 102 when the invention is used as a variable delay device. If employed, a solenoid corresponding to solenoid 20 may be excited from any suitable direct current source via connector 240 and leads 241 and 243 which are indicated in FIG. 4 as penetrating casing 110 for connection to solenoid means therewithin. When used as a pulse compression device, the solenoid may be absent, as suggested in FIG. 5.

FIGS. 5 and 6 also illustrate a further useful form 123, 124 of the transmission line means for coupling microwave signals into and out of the composite delay device. Input signals, for example, are coupled through plate 103 into ferrimagnetic rod 102 by an input coaxial-transmission-line system 123 whose inner conductor 101 is placed in close proximity to the free face of ferrimagnetic plate 103 at right angles to the axis of rod 102. Similarly, delayed microwave energy may be withdrawn from the device via an output coaxial-transmission-line system 124 whose inner conductor 105 passes in close proximity to the free face of ferrimagnetic plate 104 on the output end of ferrimagnetic rod 102.

As seen most clearly in FIG. 5, the extension conductor wire 101 of input inner conductor 121 has first and second double bends 210 and 211 which permit wire 101 to be offset and therefore aligned quite closely to the adjacent surface of quarter-wave plate 103. Thus, wire 101 is permitted to be as close as mechanically feasible to the input end of ferrimagnetic rod 102. The insertion loss of the composite delay device including rod 102 is additionally reduced by a similar configuration (not shown) for the output conductor wire 105.

As seen by reference especially to FIGS. 5 and 6, the respective input and output transmission-line systems 127 and 128 are placed at right angles to each other, again for the purpose of diminishing the direct or undelayed coupling of input signals to the output-line system 128. It will be appreciated that the orthogonal relation of transmission-line systems 127 and 128 is also an aid to generating a compact design feasible for ready manufacture. For example, in one operating form of the invention, the YIG rod 102 is about one centimeter long and three millimeters in diameter, so that the magnet gap between magnets 113 and 114 is only about 3.8 centimeters in length, with other parts of the invention having correspondingly small sizes. Thus, placement of the transmission-line systems 127 and 128 in mutually perpendicular relation permits proper isolation while still affording appropriate clearance between electrical connections and other parts of the system.

The input and output coaxial transmission line systems 123 and 124 may respectively include suitable matching structures; as in FIG. 2, these devices may take the form of known microwave coaxial transmission line low-pass or band-pass filters and it is therefore not necessary to explain their structure and operation in any detail. However, as seen clearly in FIG. 6, the input coaxial line 127 feeds energy into a conventional matching structure 125 including a continuous outer conducting wall 213 and an inner conductor 214 having portions with appropriate diameter to form impedance steps such as at 215 and 216. The inner conductor 214 and its associated parts 215 and 216 are supported within outer conductor wall 213 by the respective annular dielectric elements 217 and 218 in a manner well-known in the art.

Input and output apparatus may be respectively coupled to the transmission line structures 123 and 124 via flexible coaxial transmission lines 127 and 128. As seen in FIG. 6, the inner conductor 220 of coaxial line 127 is connected at one end of the matching system 125 to its inner conductor 214 and at its opposite end through conductor 121 to the coupling extension wire 101. The outer conductor wall 221 is likewise conductively connected via conducting wall 213 of matching element 125 to the body of casing 110.

While the invention has been described in its preferred embodiments, it is to be understood that the words which have been used are words of description rather than limitation, and that changes within the purview of the appended claims may be made without departure from the true scope and spirit of the invention in its broader aspects.

I claim:

1. A high-frequency signal delay device comprising:
casing means,
high-freqency input means lying partly within said casing means,
high-frequency output means lying partly within said casing means,
said casing means providing means for reducing direct undelayed coupling between said high-frequency input and output means,
ferrimagnetic delay means coupling said high-frequency input and output means in energy exchanging relation,
said ferrimagnetic delay means including a magnetic field responsive yttrium iron garnet portion having first and second parallel end surfaces, and
yttrium aluminum garnet quarter-wave plate means bonded to at least one of said first and second parallel end surfaces,
said yttrium aluminum garnet quarter-wave plate means being cut in such a manner that the angle between the velocity vector of the fast shear wave within said quarter wave plate and the <100> crystallographic axis of said garnet lies between substantially 2° and substantially 22.5°.

2. A high-frequency signal delay device comprising:
casing means,
high-frequency input means lying partly within said casing means,

high-frequency output means lying partly within said casing means,

said casing means providing means for reducing direct undelayed coupling between said high-frequency input and output means,

ferrimagnetic delay means coupling said high-frequency input and output means in energy-exchanging relation,

said ferrimagnetic delay means including a magnetic field responsive yttrium iron garnet portion having first and second parallel end surfaces, and

yttrium gallium garnet quarter-wave plate means bonded to at least one of said first and second parallel end surfaces,

said yttrium gallium garnet quarter-wave wave plate means being cut in such a manner that the angle between the velocity vector of the fast shear wave within said quarter-wave plate and the <100> crystallographic axis of said garnet lies between substantially 1° and substantially 22.5°.

3. A high-frequency signal delay device comprising:

casing means,

high-frequency input means lying partly within said casing means,

high-frequency output means lying partly within said casing means,

ferrimagnetic delay means coupling said high-frequency input and output means in energy-exchanging relation,

said ferrimagnetic delay means including a magnetic field responsive yttrium iron garnet portion having first and second parallel end surfaces, and

quarter-wave plate means comprising a dielectric material having a cubic lattice bonded to at least one of said first and second parallel end surfaces,

said quarter-wave plate means being cut in such a manner that the angle θ between the velocity vector therein of the fast shear wave and a <100> crystallographic axis of the dielectric material and the thickness t of the said quarter-wave plate are related by the equation:

$$t=V_f/f\,A\sin^2 2\theta$$

where:

V_f is the velocity of the fast shear wave in the dielectric material,

f is the carrier frequency of the signal to be delayed, and

A is a constant representing the complex elastic properties of the dielectric material, and the angle θ is greater than or equal to 1° and less than or equal to 22.5°.

4. A high-frequency signal delay device comprising:

high-frequency input means,

high-frequency output means,

ferrimagnetic delay means coupling said high-frequency input and output means in energy-exchanging relation,

said ferrimagnetic delay means including a magnetic field responsive portion having first and second end surfaces,

quarter-wave plate means composed of a crystalline cubic lattice material having substantially the same thermal coefficient of expansion as that of said magnetic field responsive portion of said ferrimagnetic delay means bonded to at least one of said end surfaces,

said quarter-wave plate means being cut in such a manner that the angle between the velocity vector of the fast shear wave in said quarter wave plate and the <100> crystallographic axis of said cubic lattice material is equal to or greater than 1° and equal to or less than 22.5°.

5. Apparatus as described in claim 4 wherein said quarter-wave plate means is comprised of a material selected from the class of dielectric garnet materials including yttrium aluminum garnet and yttrium gallium garnet.

6. Apparatus as described in claim 5 wherein said magnetic field responsive portion comprises yttrium iron garnet.

7. Apparatus as described in claim 6 comprising magnetic field generation means for generating a predetermined magnetic field within said magnetic field responsive portion.

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