Feb. 28, 1967 R. T. DENTON ET AL 3,307,120

ULTRASONIC WAVE DEVICE

Filed Sept. 26, 1962

FIG. 1

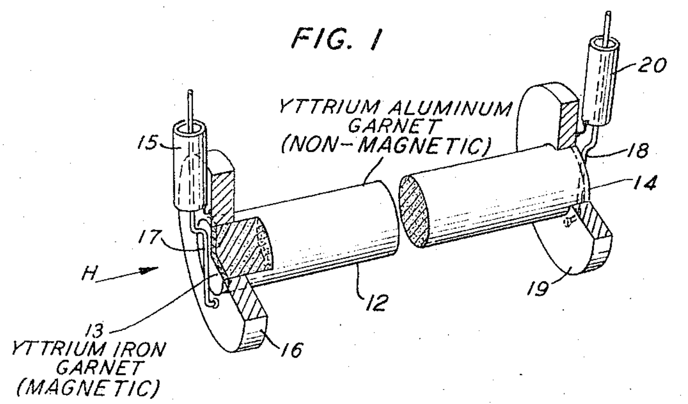
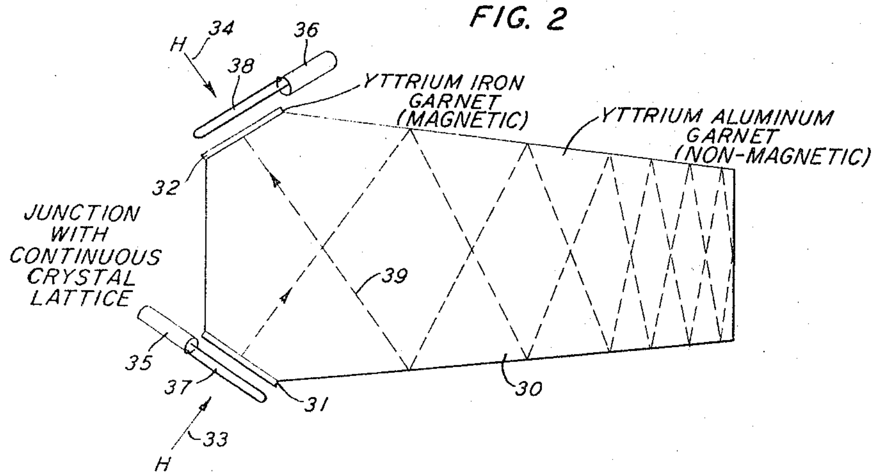



FIG. 2




INVENTORS R. T. DENTON
E. G. SPENCER

BY Roy M. Porter Jr.

ATTORNEY

United States Patent Office

3,307,120

Patented Feb. 28, 1967



3,307,120

# ULTRASONIC WAVE DEVICE

Richard T. Denton, South Plainfield, and Edward G. Spencer, Berkeley Heights, N.J., assignors to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

Filed Sept. 26, 1962, Ser. No. 226,381
10 Claims. (Cl. 333—30)

This invention relates to ultrasonic delay line devices and more particularly to the construction of efficient magnetic transducers for these delay lines.

Recently it has been recognized that small elements of certain magnetically polarized materials of the types which exhibit gyromagnetic effects may be employed as generators for ultrasonic vibrations at microwave frequencies. The element is biased by a direct-current magnetic field and the microwave frequency magnetic field is introduced perpendicular to the biasing field. By what presently appears to be a complicated mixture of gyromagnetic precession and magnetostriction, an ultrasonic wave will be produced in the material which will be transferred into a connected delay medium. Analysis of certain aspects of the involved phenomenon may be found in articles by C. Kittel in 110 Physical Review 836, May 15, 1958; Brommel and Dransfeld in 3 Physical Review Letters 83, July 15, 1959; Schlomann in 31 Journal of Applied Physics 1647, September 1960; and Spencer, Denton and Chambers in 125 Physical Review 1950, March 15, 1962.

It has been proposed that the gyromagnetic element, which preferably takes the form of a thin disc, be bonded to a delay medium constructed by conventional delay line material. These bonds can be made to transmit ultrasonic energy efficiently at low frequencies but at frequencies roughly above 100 megacycles per second these bonds introduce large insertion losses between the transducers and the delay medium with a consequent inefficiency. Alternatively, it has been proposed to form the delay line itself as well as the transducer from the same member of gyromagnetic material. A biasing field and a radio frequency field are applied so that an end surface or end film of the member constitutes the transducer. While such a homogeneous construction eliminates the bond, it has been found that the biasing field incidently magnetizes the entire member of magnetic material and becomes a relatively inefficient propagation medium for the ultrasonic waves due to its gyromagnetic losses. It has been further recognized that the polarized nature of the magnetized propagation medium has undesirable effects upon propagation through it in any direction other than one parallel to the applied field direction.

It is therefore an object of the present invention to increase the efficiency and flexibility of ultrasonic delay line devices employing magnetic transducers.

In accordance with the present invention, the delay line is composed of a nonmagnetic material having a crystal structure and unit cell size similar to that of the magnetic transducer material, with the transducer material grown epitaxially upon the delay line material. Thus, the delay line together with its transducer constitutes a single extended crystalline lattice, a portion of which is magnetic and the remainder of which is nonmagnetic. Specific examples to be described include magnetic yttrium iron garnet grown upon a delay line of nonmagnetic yttrium aluminum garnet or yttrium of gallium garnet, or magnetic magnesium iron oxide grown upon magnesium aluminate.

A feature of the invention resides in the particular coupling circuit employed to support and apply the radio frequency magnetic field to the magnetic transducer portion.



These and other objects, the nature of the present invention, its various features and advantages will appear more fully upon consideration of the various illustrative embodiments now to be described in detail in connection with the accompanying drawings, in which:

FIG. 1 is a perspective view, partly in cross-section of a delay line interconnected between a pair of transducers in accordance with the invention; and

FIG. 2 illustrates the application of the invention to a multiple reflection form of relay device.

Referring more particularly to FIG. 1, an illustrative embodiment of the invention is shown comprising a delay line in the form of a cylindrical rod **12** formed from a single crystal of nonmagnetic material and transducer layers **13** and **14** formed upon each of its ends as a continuation of the same crystal lattice from a nonconductive, magnetic material of the type having substantial gyromagnetic properties. The nature of both the magnetic and nonmagnetic materials will be described in more detail hereinafter. The dimensions and crystalline orientation of rod **12** are selected to produce the desired ultrasonic delay and mode of propagation at the frequency of interest. Radio frequency energy at microwave frequencies is coupled into and out of layers **13** and **14** by a novel coaxial coupling. Thus, an input coaxial line **15** located adjacent to layer **13** with the outer conductor electrically and mechanically connected to conductive ring **16** which surrounds the end of rod **12** and layer **13**. The center conductor **17** of coax **15** passes across the face of layer **13** and electrically terminates on the opposite side of ring **16**. Ring **16** serves the dual function of providing a rigid support for coax **15** and rod **12** and also serves as the ground plane for the radio frequency fields supported between conductor **17** and ring **16** by means of which a circularly polarized component of radio frequency magnetic field is excited in the plane of layer **13**. A direct-current biasing field is applied by means not illustrated in detail in a direction normal to the plane of layers **13** and **14**. This field is represented schematically by the vector H and has a strength that biases the gyromagnetic material of layers **13** and **14** into the neighborhood of ferromagnetic resonance. As a result of a mixture of the gyromagnetic precession about the biasing field and magnetostriction as described in the abovementioned publications, circularly polarized acoustical waves are excited in layer **13** and are transferred to rod **12** through which they travel to the output transducer comprising layer **14**, conductor **18** and ring **19** by which the energy is reconverted into a microwave signal upon coax **20**.

A principal feature of the present invention resides in the nature of the material comprising the transducer layers **13** and **14**, the material of rod **12** and the juncture therebetween. The material of each layer is preferably one of the known nonconducting magnetic materials which exhibits gyromagnetic properties at microwave frequencies and which, in addition, has reasonably low magnetic losses, large magnetoelastic coupling constant, high acoustical Q and may be grown in single crystal form. One of the most suitable materials for this purpose is yttrium iron garnet. Having thus selected the gyromagnetic material which is to constitute the transducer, the material to form rod **12** is then particularly chosen in accordance with the principles of the present invention. Thus, the material for rod **12** is one that has a similarity in both crystalline structure and unit cell size to that of the gyromagnetic material so that the gyromagnetic material may be epitaxially grown upon the cylindrical end of the rod as a continuation of the crystal lattice thereof. In particular, when yttrium iron garnet is employed as the gyromagnetic material, a single crystal of nonmagnetic yttrium aluminum garnet is preferred for rod **12**. Other combinations of magnetic and nonmagnetic materials will be set forth hereinafter.

Several methods for epitaxially depositing materials of the types here considered are familiar to the art and it appears necessary only to summarize one particularly suitable method for the purpose of the present disclosure. In general, the process is similar to the seeded flux growths heretofore employed to grow single crystal magnetic materials. The primary difference resides in the fact that for the present process the "seed" comprises the substrate member of nonmagnetic material constituting the delay media. Typically, the process includes the steps of combining the reactants of the magnetic material to be grown in the proper proportions with a flux comprising lead oxide, lead borate, lead fluoride, boron oxide or combinations thereof, heating the mixture to form a homogeneous solution of the reactants, inserting the seed crystal, and cooling the mixture very slowly to room temperature. Further details of these processes may be found in Patents 2,957,827 and 3,050,407 granted to J. W. Nielsen, October 25, 1960, and August 21, 1962; or in the copending application of J. P. Remeika, Serial No. 28,862, filed May 13, 1960.

In particular, to grow layer 13 of yttrium iron garnet epitaxially upon rod 12 of yttrium aluminum garnet, the reactants yttrium oxide and iron oxide are weighed, mixed together and placed in a suitable crucible along with a flux such as lead oxide. The crucible is heated to fuse the flux and reactants and to form a homogeneous melt. A temperature of approximately 1200° F. appears satisfactory. The end of rod 12, which has been squared and polished, is lowered into the melt and the temperature is reduced. Thereupon yttrium iron garnet will begin to form upon the yttrium aluminum garnet rod as a continuation of the crystal lattice of the substrate. Cooling is continued until the growth is sufficient to produce a layer thickness that is on the order of at least one-half a wavelength of the intended ultrasonic frequency. Typically, this occurs after a temperature reduction of several hundred degrees. The rod 12 is then removed, cooled to room temperature whereupon the layer is shaped and polished to the precise thickness desired.

The preceding discussion has been directed specifically to the combination of yttrium iron garnet and yttrium aluminum garnet as the transducer and delay line materials, respectively. These materials are among the familiar and useful magnetic and nonmagnetic compounds having the garnet structure. Like aluminum, however, gallium and other Group III elements may be substituted for the iron in the basic garnet structure to produce a nonmagnetic material. Note, however, that aluminum and gallium produce crystals of unit cell size most similar to iron and are, therefore, most readily epitaxially grown upon each other by present techniques.

Another structural class of magnetic and nonmagnetic materials that may be used to practice the present invention comprise those of spinel crystalline structure. Of this class, magnesium iron oxide has pronounced gyromagnetic properties and has been successfully grown upon a substrate of magnesium aluminate. This class appears to be particularly attractive from an economical standpoint because of the well known lower cost of the material and processing for the spinels as compared to the garnets. It is also possible by processes well known for the spinels to produce a gradual single crystal transition from nonmagnetic to magnetic composition.

Other magnetic and nonmagnetic constituents may, of course, be added as is the practice in the art to improve the properties of either the magnetic or nonmagnetic portions. In the case of the garnet class this includes materials formed from rare earth elements other than yytrium. Therefore, the present invention contemplates a member having a single crystalline lattice structure, a portion of which is magnetic and includes a magnetic constituent such as iron and the remainder of which is



nonmagnetic and includes instead nonmagnetic constituents such as aluminum.

The term "epitaxial" as used herein should be understood in its broadest sense as designating a process by which one material is grown or deposited upon a base material that is somewhat different, either in terms of composition, impurity content, or other property, and in which the grown material is deposited in a crystal structure, the orientation of which is determined by the crystal orientation of the base material to form with a base a continuous crystal lattice. It includes, in addition to the flux growth process described above, those processes referred to in the art as hydrothermal synthesis, flame fusion and equivalent processes. In addition, a diffusion process may be employed by which sufficient quantities of magnetic material are added into the crystal structure of the nonmagnetic base to produce a magnetic layer therein.

The present invention represents an improvement over either a magnetic transducer bonded to conventional nonmagnetic delay line or a homogeneous magnetic structure in which both transducer and delay line are formed from the same magnetic crystal. As to the first, the epitaxially formed junction according to the present invention provides a rigid, unitary connection without the mechanical problems of the bond. Further, since the interface between the transducer material and the delay line material is a continuation of the same crystal lattice, ultrasonic energy can be efficiently transferred across it even at microwave frequencies. As to the second prior art form, the difficulty and expense of growing single crystals of magnetic material are reduced by the use of more easily grown nonmagnetic materials as the delay line. Moreover, a magnetic delay medium, particularly in the presence of the residual biasing field which extends into it from the transducer and may bias it in the vicinity of gyromagnetic resonance, has substantially greater acoustical propagation losses than nonmagnetic materials.

The principles of the present invention are particularly advantageous when applied to any of the various forms of polygonal or multifacet delay lines in which the ultrasonic wave is multiply reflected from a plurality of faces. The reason for this advantage will be apparent from FIG. 2 which shows a polygonal body 30 in one of the preferred forms as described in Patent 2,839,731 granted June 17, 1958, to H. J. McSkimin. Ultrasonic wave energy launched within body 30 is multiply reflected as represented by path 39 until it returns to the output transducer.

In accordance with the present invention, body 30 is formed from a crystal of nonmagnetic material of the type described above and is shaped according to the teachings of the above-mentioned McSkimin patent. Alternative shapes may be found in the teachings of D. L. Arenberg, 20 Journal of Acoustical Society 1, 1948. The input and output transducers comprise layers 31 and 32 of gyromagnetic material which are epitaxially formed upon the selected faces of body 30. The radio frequency input and output are illustrated schematically by coaxial conductors 35 and 36 ending in loops 37 and 38, respectively, with the plane of the loops oriented normal to the faces of the respective layers 31 and 32. Steady biasing fields represented by vectors 33 and 34 are applied respectively to layers 31 and 32 in a direction normal to the plane of each layer.

It will be readily apparent that if body 30 were formed of magnetic materials, as in the case of the homogeneous magnetic construction of the prior art, the presence of steady biasing fields 33 and 34 of the transducers would extend also into body 30, magnetically polarizing body 30 along the axes of the fields and thereby destroying its cubic symmetry. The multiply reflected ultrasonic waves which necessarily cross these polarized axes at random angles will be greatly distorted and dispersed due to the preference of the ultrasonic wave to propagate parallel to the polarized axes. However, since body **30** is nonmagnetic when constructed according to the invention, its symmetrical nature is unaffected by magnetic fields.

In all cases it is to be understood that the above-described arrangements are merely illustrative of a small number of the many possible applications of the principles of the invention. Numerous and varied other arrangements in accordance with these principles may readily be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

**1.** An ultrasonic delay device comprising a member having a transducer portion formed of magnetic material and a delay line portion formed of nonmagnetic material, means including means for applying a radio frequency magnetic field to said magnetic portion for generating ultrasonic wave energy and means for utilizing ultrasonic wave energy connected to said nonmagnetic portion, said magnetic and nonmagnetic materials both being single crystal materials of given crystal lattice structure, the junction between said portions being formed as a continuous crystal lattice structure extending from and including the crystal lattice of said magnetic portion to and including the crystal lattice structure of said nonmagnetic portion so that no acoustical discontinuity is presented to said wave energy traversing said junction.

**2.** An ultrasonic device according to claim **1** wherein said magnetic material is yttrium iron garnet and wherein said nonmagnetic material is yttrium aluminum garnet.

**3.** An ultrasonic device according to claim **1** wherein said magnetic material is magnesium iron oxide and wherein said nonmagnetic material is magnesium aluminate.

**4.** An ultrasonic device of the type in which a transducer including an element of magnetic materials suitably excited to generate ultrasonic wave energy is mechanically coupled to a delay line for conveying said generated elastic wave energy away from said transducer characterized in that the material of said delay line is nonmangetic and has a crystal shape that is the same as the crystal shape of said magnetic material and a crystal lattice structure and unit cell size that are similar to the crystal lattice structure and unit cell size of said magnetic material.

**5.** An ultrasonic device according to claim **4** wherein said magnetic material and said nonmagnetic material both form a single continuous crystal lattice.

**6.** An ultrasonic device according to claim **4** wherein said magnetic material is a compound including iron in a given crystalline structure and wherein said nonmagnetic material is a compound including an element from Group III in said given crystalline structure.

**7.** An ultrasonic device comprising a member of nonmagnetic material having a crystal structure and unit cell size for receiving and transmitting ultrasonic wave energy,



a layer of magnetic material having a crystal structure and unit cell size similar to that of said member formed epitaxially upon a surface of said member, means for applying a steady magnetic field to said layer and means for applying a high frequency radio magnetic field to said layer in a direction normal to said steady field for converting said high frequency field into an ultarsonic wave for transmission into said nonmagnetic member.

**8.** An ultrasonic device according to claim **7** wherein said means for applying said high frequency field comprises a ring of conductive material surrounding said layer and a two-conductor transmission line for said energy having one conductor thereof connected to said ring on one side of said layer, the other conductor thereof extending across said layer and being connected to said ring on the other side of said layer.

**9.** An ultrasonic device according to claim **7** wherein said nonmagnetic member comprses yttrium aluminum garnet and wherein said magnetic layer comprises yttrium iron garnet formed as a continuation of the crystal structure of said nonmagnetic member.

**10.** An ultrasonic delay device comprising a member having at least an end portion which is of magnetic material of the type which exhibits gyromagnetic properties at high frequencies, means utilizing said gyromagnetic properties for generatng ultrasonic wave energy at said high frequencies comprising a ring of conductive material surrounding said end portion, a two conductor transmission line for high frequency radio energy having one conductor thereof connected to said ring on one side of said portion, the other conductor thereof extending across said portion and being connected to said ring on the other side of said portion, means for applying high frequency radio energy between said conductors, and means for applying a steady magnetic field to said portion in a direction normal to said other conductor, and means for conveying said generated elastic wave energy away from said portion.

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HERMAN KARL SAALBACH, *Primary Examiner.*

C. BARAFF, *Assistant Examiner.*