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Morgenthaler

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[54] **TUNABLE VARIABLE BANDWIDTH MAGNETO-ELASTIC FILTER AND METHOD**

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[52] **U.S. Cl.** ..... **333/71,** 333/73 R

[51] **Int. Cl.** **H03h 9/34,** H03h 7/08

[58] **Field of Search** ..... 333/30 M, 71, 73 R

[56] **References Cited**

UNITED STATES PATENTS

3,593,215	7/1971	Moore	333/30 M
3,668,568	6/1972	Morgenthaler	333/71 X
3,670,271	6/1972	Vasile	333/30 M

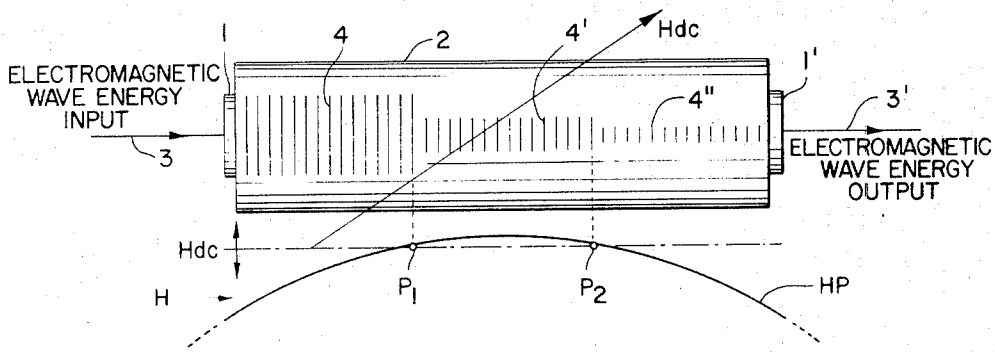
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[57] **ABSTRACT**

This disclosure involves one or a plurality of cascaded YIG or similar magneto-elastic media propagating elastic waves transduced from a band of electromagnetic waves and having special magnetic field curved profiles and variable bias magnetic fields applied thereto such as to couple out or absorb the energy of specified variable frequencies to-be-filtered, by effecting conversions of the elastic waves of such specified frequencies only to spin waves. Cascaded units enable a bandpass characteristic to be produced that may be varied in width and center frequency.

19 Claims, 8 Drawing Figures



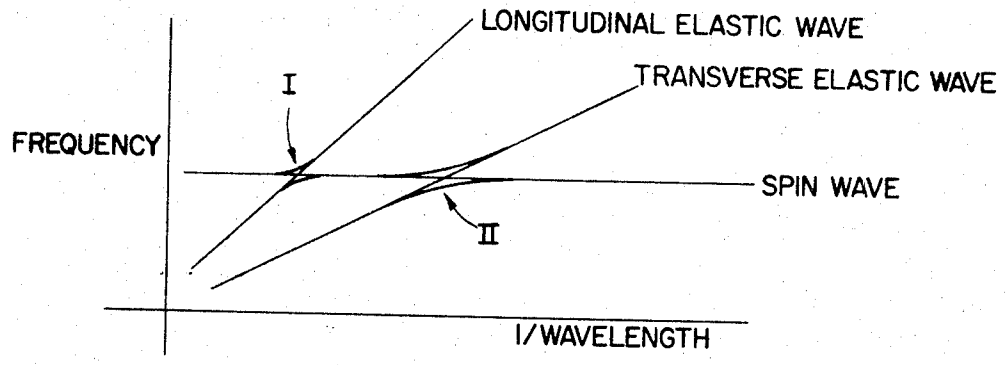


FIG. 1

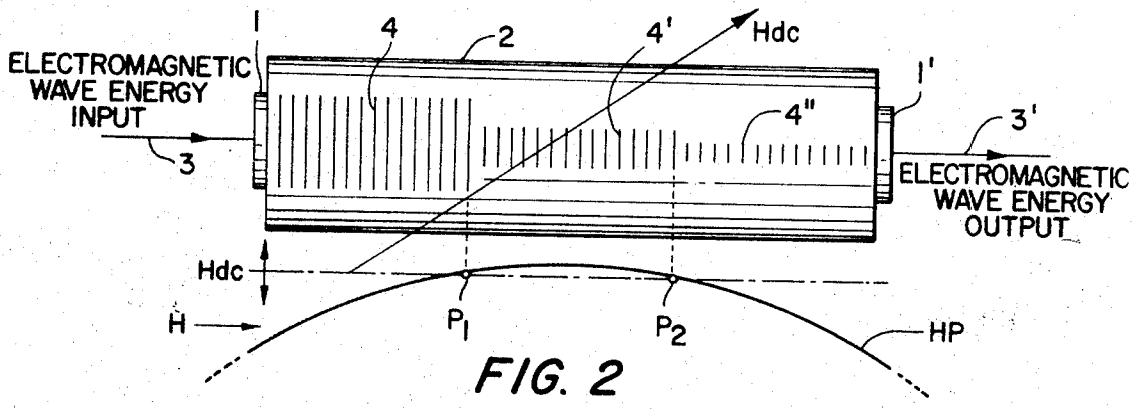


FIG. 2

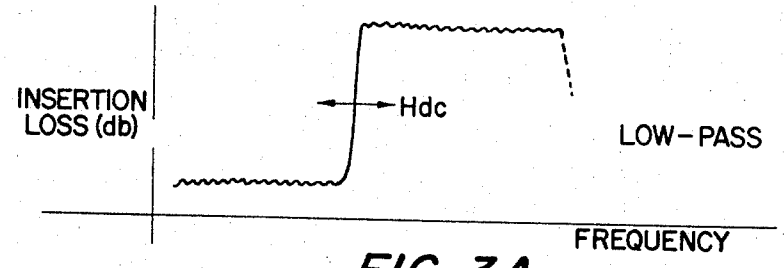


FIG. 3A

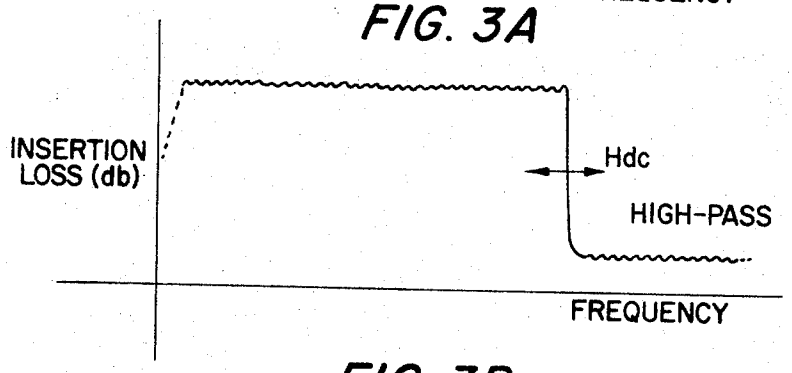


FIG. 3B

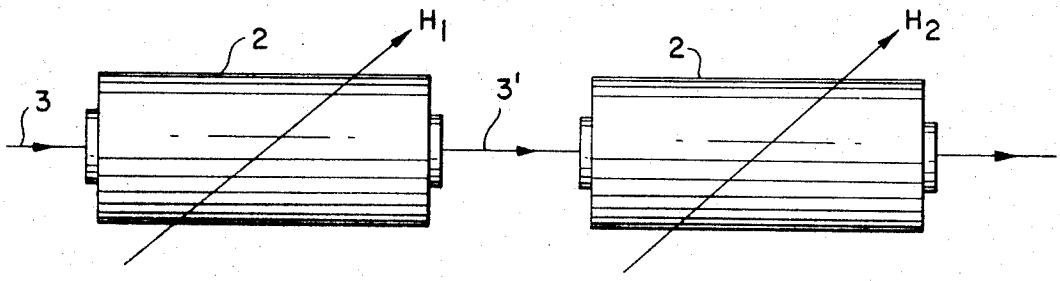


FIG. 4A

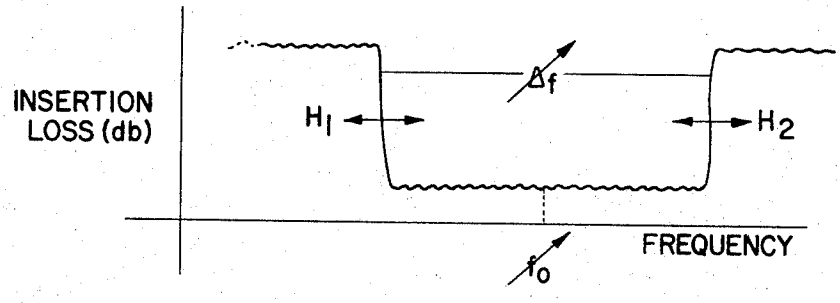


FIG. 4B

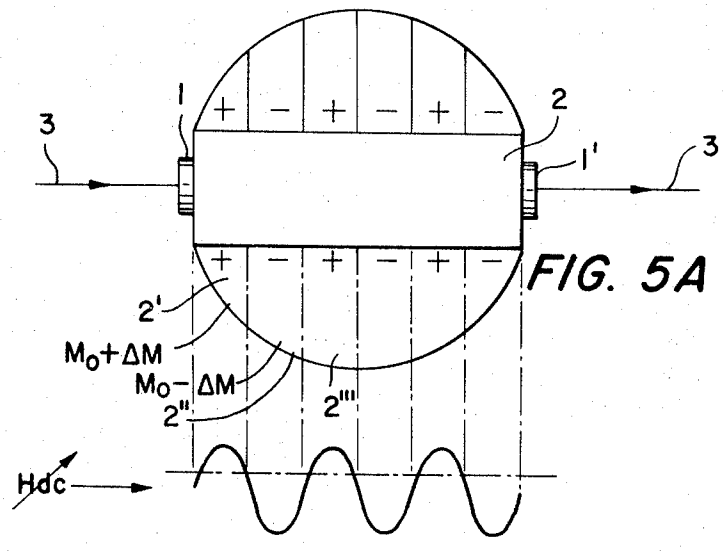


FIG. 5A

FIG. 5B

TUNABLE VARIABLE BANDWIDTH MAGNETO-ELASTIC FILTER AND METHOD

The present invention relates to magneto-elastic filter structures and methods, being more particularly directed to YIG and similar crystal devices operated as electronic filter devices.

As described, for example, originally by R.W. DeGrasse, J. Appl. Phys. Vol. 30, No. 4, April 1959 Edition, Pg. 155S "Low-Loss Gyromagnetic Coupling through Single Xtal Garnets", YIG filters have been proposed, and, as described in IRE Transactions on MTT, May 1961 Edition, Pgs. 252–260, Philip S. Carter, Jr., "Magnetically-Tunable Microwave Filters Using Single-Crystal Y-I-G Resonators," have now been widely employed as signal preselectors in frequency swept receivers of signal processing applications since they are high "Q" devices that can be rapidly frequency-tuned by magnetic means.

There are, however, a number of areas of performance limitations in such devices. Tracking filters of this nature, for example, often employ up to four sections, since there is a basic limitation on the maximum selectivity that can be obtained per section. Attainment of higher selectivity is very difficult because of the severe engineering problems encountered in trying to make all sections track together over a wide range of frequencies, especially in the presence of temperature variations. Conventional YIG filters, moreover, have narrow bandpass (or band rejection) characteristics that are essentially independent of frequency. Although this may be satisfactory for many applications, it is sometimes desirable to be able electronically to control the bandwidth of such filters. Such conventional filters, furthermore, are subject to high power limitations which, in turn, limit power level and the available dynamic range.

An object of the present invention, accordingly, is to provide a new and improved filter and method embodying magneto-elastic media, such as YIG crystals, that enable electronically tunable variable-bandwidth filtering and overcome the disadvantages and limitations above described.

A further object is to provide a novel magneto-elastic filter of more general applicability, as well.

Other and further objects will be explained hereinafter and are more particularly delineated in the appended claims. In summary, however, from one of its broader aspects, the invention contemplates the use of novel magnetic field profile curves and intersecting bias magnetic fields that enable absorption of specified frequencies only, by effecting the conversion of elastic waves corresponding to such specified frequencies only to spin waves within the medium. Preferred details are hereinafter set forth.

A filter constructed in accordance with the invention, in general, consists of a low-loss single crystal YIG or the like having a maximum dimension several millimeters long. The crystal is electronically biased and fitted with appropriate input and output transducers capable of converting, for example, microwave electromagnetic energy to elastic wave form, such as longitudinal elastic waves. When the crystallographic axes are specially oriented and the magnetic bias is properly chosen, the insertion loss of the device becomes a strong function of frequency above (or below) some characteristic frequency or frequencies as the corresponding elastic wave frequency becomes converted to a spin wave. This function can be made very abrupt in the vicinity of such a frequency so as to yield, in effect, an absorption edge. Moreover, these specified characteristic frequencies can be moved at will by altering the electronic bias of the bias field. If two such elements are cascaded and controlled with separate biases, a bandpass characteristic can be formed between two absorption edges; and the bandwidth and band center or center frequency are then separately variable. The filter characteristic, moreover, can rapidly be changed so as to yield either bandpass, lowpass, highpass or a combination of these. Wide or narrow band rejection is also possible.

Because the wave energy transmitted through the crystals is elastic power, furthermore, it is not subject to the high power nonlinearities asssociated with conventional tunable YIG filters. It is, therefore, possible to employ input powers as high as one watt, for example, before the input transducer is threatened with breakdown. The filtered output additionally is nondispersively delayed--typically, a few microseconds.

The invention will now be illustratively described with reference to the accompanying drawing, of which

FIG. 1 is a graph illustrating the elastic-wave-to-spin wave splitting or conversion phenomenon underlying the invention;

FIG. 2 is a schematic diagram of a filter operating in accordance with the method of the invention;

FIGS. 3A and 3B are explanatory insertion loss or filter performance graphs;

FIG. 4A is a diagram similar to FIG. 1 of a modification, and FIG. 4B is a graph illustrating the filter action thereof; and

FIG. 5A is a diagram similar to FIG. 1 of a preferred structure, with FIG. 5B illustrating the magnetic profile curve thereof.

Referring to FIG. 1, plotting frequency as a function of inverse wavelength, as described, for example, in Applied Physics Letters, Vol. 16, Feb. 1, 1970, p. 133, the conversion or splitting of longitidunal and transverse (or shear) elastic waves in magneto-elastic media, such as YIG crystals and the like (including Ga and/or Mn-doped YIG, Li-Ferrite, Eu-doped YIG, for example), into spin waves involves a much smaller frequency splitting region I for the faster longitudinal waves, than for the transverse or shear waves (II) customarily employed in prior art apparatus of this character. For the filtering purposes of the present invention, where it is desired to obtain such conversion abruptly over the narrowest possible frequency range (theoretically at a single frequency), the longitudinal elastic waves have been found to be decidedly preferred. Longitudinal elastic-wave transducers are accordingly shown at 1 and 1', FIG. 2, such as CdS, ZnO, or similar piezoelectric electrode-provided layers or the like, for example, as described in Microwave Theory and Techniques, November, 1969, Vol. MTT-17, No. 11, applied to opposed edges of a YIG or similar magneto-elastic medium 2. Electromagnetic wave energy, such as, for example, S-band or other microwave frequencies, is applied as an input 3 to the transducer 1 to effect conversion or transduction into longitudinal elastic waves (represented by the vertical wave fronts 4), propagated into and longitudinally across the medium 2. Whatever elastic wave energy is transmitted to the output transducer 1' is reconverted into electromagnetic energy and extracted at the output 3'.

In accordance with a discovery underlying the present invention, if an appropriate cut and orientation of crystal is employed, and a proper direction of magnetic field H applied, such as, for example, when symmetry axis, field direction and propagation direction all are colinear and lie in a (**110**) plane at an angle of 25.52° from a [**100**] direction, a magnetic field profile may be set up across the medium **2** having the curved rising and then falling characteristic HP shown immediately below the medium **2**, successive points of the curve HP corresponding to successive points along the medium **2**. By proper adjustment of a bias magnetic field H_{dc} applied to the medium **2**, in this case, and of appropriate magnitude, illustrated by the horizontal dash-dot line H_{dc}, one can select the points P_1 and P_2 of intersection with the magnetic field profile curve HP. These points correspond to regions, shown immediately above in the medium **2**, at which the particular elastic wave frequency represented by the delay time at such regions within the medium **2**, have been found selectively to be split-converted (I, FIG. **1**) into spin waves with attendant higher insertion loss or absorption of the energy, leaving a greatly reduced amplitude of elastic wave energy of such frequency to continue through the medium at **4'**. Similar comments apply at P_2 and **4''**. The resulting step or abrupt coupling-out or filtering-absorption from the band of frequencies transmitted between **1** and **1'** of such particular frequencies only, is illustrated by the almost vertical-line portion of the insertion loss vs. frequency characteristic of FIG. **3A** - - a low-pass absorption edge; and with an appropriately shaped magnetic profile curve HP, high-pass absorption cut-off, represented by the vertical line of graph FIG. **3B**, may be similarly attained. By adjusting or varying the value of H_{dc}, as by conventional electromagnet field controls (schematically represented by the variable arrows and orienting the same at the desired inclined or other angle to the axis of the medium **2** or direction of propagation of the elastic waves therein), thus, the specified frequencies to be filtered out may be readily varied or tuned in the structures of the invention.

A bandpass characteristic, as shown in FIG. **4B**, can readily be achieved, moreover, by cascading two such systems **2, 2**, etc., as illustrated in FIG. **4A**. Variation of either of the different fields H_1 and H_2 of the successive units will thus cause variation or tuning of the center frequency f_o of the filtered band; and variation of both fields will readily vary the bandwidth Δf.

It is desirable for increased selectivity and insertion loss or absorption at the desired specified frequencies, to provide a plurality of points P of intersection with the magnetic field profile, though this must be compromised with the bandwidth, since the amplitude of the ripple in field amplitude decreases as the number of ripples increases in the case of external magnetic poles. Where the magnetic poles are internally distributed, as, for example, when the crystal is appropriately doped with a special dopant variation, this limitation does not apply. The structure of FIG. **5A** was designed, accordingly, to give the multiple rising-falling profile of FIG. **5B**, embodying a single YIG crystal of saturation magnetization M_o surrounded by polycrystal YIG portions **2'**, **2''**, **2'''**, etc. of different heights, formed substantially circularly thereabout, as in the form of discs, sleeves, beads or layers. The successive portions **2'**, **2''**, **2'''**, etc. are represented by respective +, −, etc. pole signs, indicating different saturation magnetization values $M_o+\Delta M$, $M_o-\Delta M$, $M_o+\Delta M$, etc., resulting in the profile of FIG. **5B**.

The structure of FIG. **5A** has been successfully operated to produce the above results. A YIG rod **2** about 1 centimeter long and 3 millimeters in diameter was used, cut with its symmetry axis parallel to a cube-faced diagonal (**110** axis). The magnetic field Hdc was applied at an angle of about 40° inclined to the longitudinal or elastic-wave-propagation axis and adjusted up to about 1,500 oersteds, with electromagnetic energy applied at **1** in the frequency range of 1 to 2 GHz. The unit **2** had six external sleeves **2'**, **2''** etc. as in FIG. **5B**. A ratio of insertion loss in the leading edge of 35 to 40 db was obtained having its stepped slope occurring over about 30 MHz, representing a selectivity of between 18 and 24 db per octave. This is as compared with the 6 db per octave obtainable with each section of conventional YIG filters. The leading edge of the insertion loss characteristic was successfully tuned or swept over the whole 1 to 2 GHz band or range by adjustment of the value of Hdc between about 550 and 1100 oersteds. Without the external alternately poled portions **2'**, **2''**, etc., the same crystal **2** alone, operated with the same orientation of magnetic field Hdc and the same frequency range was found to produce selectivity also as high as about 20 db, though lesser values were also obtained, with selectivity bands being produceable and tunable with very narrow characteristics of the order of 10 MHz up to much wider bands of the order of 300 MHz and greater values.

In summary, therefore, the results attainable with the invention include the following advantages which are contrasted with prior conventional YIG and related preselector filters before-described:

1. The band center and bandwidth can be separately electronically controlled. There are indications that very high selectivity is possible without cascading more than two filter sections.

2. Lowpass, highpass and bandpass (rejection) designs are possible. In fact, in the same unit, it is possible electronically to switch from one filter mode to another (within the same basic frequency range).

3. The filters are not subjected to high power nonlinearities for inputs below the order of one watt.

4. More than one set of input and output transducers can be attached to the crystal and arranged so that the characteristic filter frequencies for each independent channel differ — yet track systematically when the electronic bias is swept. The effect is to have several different filters ganged together that one can simultaneously process either the same input signal or several different ones.

5. The filtered output will be non-dispersively delayed from the input by a fixed amount — typically, a few microseconds.

6. The maximum tuning range available with a single filter is limited by the input and output transducer bandwidth — generally on the order of an octave.

Further modifications will also occur to those skilled in this art, and all such are considered to fall within the spirit and scope of the invention as defined in the appended claims.

What is claimed is:

1. A method of filtering out specified frequencies from a band of electromagnetic wave frequencies, that comprises, transducing the electromagnetic wave fre-

quencies into corresponding elastic waves, propagating the elastic waves through a magneto-elastic medium, re-transducing the propagated elastic waves back into electromagnetic waves after passage through said medium, applying a magnetic field curved profile and bias magnetic field to said medium, the former of such shape and orientation that the bias magnetic field applied to the medium will intersect such profile at points corresponding to predetermined regions of the medium in turn corresponding to the specified frequencies to be filtered out, the field at such regions effecting conversion of the elastic waves of the specified frequencies only to spin waves with attendant absorption of the energy thereof, and varying the bias magnetic field to vary the position of said regions and thus to vary specified frequencies to be filtered out.

2. A method as claimed in claim **1** and in which said profile and bias field are caused to intersect at a plurality of regions along said medium.

3. A method as claimed in claim **1** and in which the profile curve rises and then falls along said medium.

4. A method as claimed in claim **1** and in which the profile curve falls and then rises along said medium.

5. A method as claimed in claim **1** and in which said medium comprises YIG material.

6. A method as claimed in claim **1** and in which said elastic waves are longitudinal elastic waves.

7. A method as claimed in claim **1** and in which said bias field is applied substantially parallel to the direction of propagation of the elastic waves in said medium.

8. A method as claimed in claim **1** and in which said bias field is applied at an angle inclined to the direction of propagation of the elastic waves in the medium.

9. A method as claimed in claim **1** and in which the steps of claim **1** are then repeated in a cascaded second magnetic-elastic medium with different magnetic fields to form a bandpass characteristic between the spin-wave-converted absorption frequencies of the media, and varying said fields to vary at least one of the width and center frequency of such bandpass.

10. A method as claimed in claim **1** and in which successive portions of said medium are provided with different saturation magnetization.

11. A tunable electromagnetic wave filter having, in combination, a magneto-elastic medium provided at opposing surfaces with electromagnetic energy-to-elastic wave energy transducers, means for applying a band of electromagnetic wave frequencies to one transducer to convert the same to corresponding elastic waves that may then propagate through the medium to the other transducer at which the elastic waves are reconverted back into electromagnetic waves, means for applying to the medium a magnetic field curved profile and bias magnetic field that intersects the same at points corresponding to specified frequencies of said band, the field at such regions effecting conversion of the elastic waves of the specified frequencies only to spin waves with attendant absorption of the energy thereof, and means for varying the bias magnetic field to vary the position of said regions and thus to vary the specified frequencies to be filtered out.

12. A filter as claimed in claim **11** and in which said medium comprises YIG material.

13. A filter as claimed in claim **11** and in which said field applying means is adjusted to produce a profile curve that rises and then falls along the medium.

14. A filter as claimed in claim **11** and in which said field applying means is adjusted to produce a profile curve that falls and then rises along the medium.

15. A filter as claimed in claim **11** and in which said field applying means is adjusted to produce a profile curve that rises and falls a plurality of times along the medium.

16. A filter as claimed in claim **11** and in which said transducers are electromagnetic energy-to-longitudinal elastic wave transducers.

17. A filter as claimed in claim **11** connected in cascade with a second similar filter but with a different magnetic field.

18. A filter as claimed in claim **11** having successive portions of said medium of different saturation magnetization values.

19. A filter as claimed in claim **11** having a central YIG crystal medium externally provided with a plurality of poly-crystal YIG portions of greater and lesser saturation magnetization values.

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