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[54] SIGNAL PROCESSING APPARATUS

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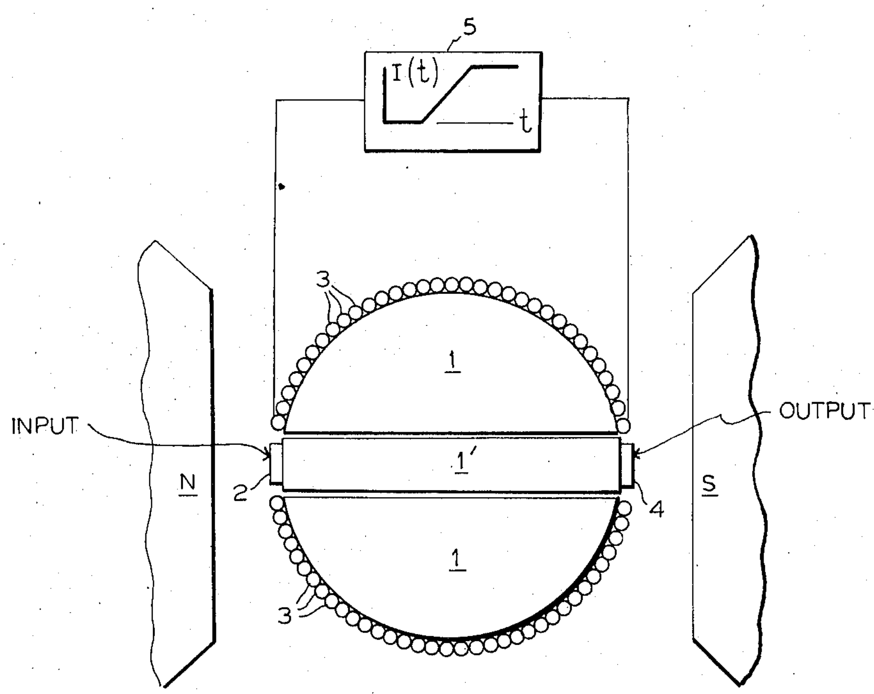
[57] **ABSTRACT**

This disclosure involves a novel and compact pulse compression filter and the like, employing elastic shear-wave, spin-wave, longitudinal-wave transduction by means of a time-varying magnetic bias field, providing increased power handling capability and greater compression ratios than present-day filters.

19 Claims, 1 Drawing Figure



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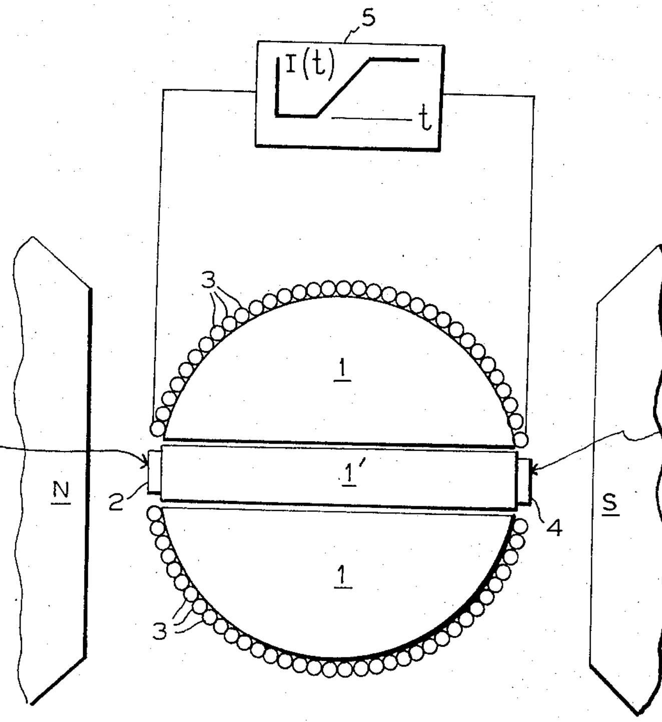

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SIGNAL PROCESSING APPARATUS

The present invention relates to signal-processing apparatus, being more particularly, though not exclusively, directed to producing controlled frequency-dispersive time delay including time compression, expansion, inversion or other delay of electric impulses preferably of the type involving frequency-modulated impulses, such as so-called "chirp" pulses and the like useful in radar and similar applications, as described, for example, in the Proceedings of the IEEE, Vol. 56, No. 3, March, 1968, pages 273–285.

Numerous types of signal-processing filters have been proposed and used for such purposes, including magnetostrictive delay lines, as described in said Proceedings, electric networks and other devices. All such techniques, however, have heretofore had serious limitations in power-handling capability, in achievable pulse compression (or expansion) ratios, and in application to wideband systems.

It is thus to the obviating of these limitations that the present invention is primarily directed; it being an object of the invention to provide a new and improved signal-processing apparatus of this character that has vastly increased power-handling, pulse-compression ratio, and wideband capabilities.

A further object is to provide a new and improved time signal-processing filter apparatus of more general utility, also, as well as a novel method or signal processing.

An additional object is to provide new and improved signal-delay apparatus.

Other and further objects will be hereinafter explained and more fully delineated in the appended claims. In summary, however, from one of its broad aspects the invention contemplates an electric-impulse signal-processing apparatus having, in combination, an elastic-wave-supporting device, input and output transducer means disposed at the device for respectively coupling electric impulses thereto to generate and propagate elastic waves therein and for transducing such waves into electric output impulses, and means for applying a time-varying energy field to the device during the coupling of said electric impulses into the device by the input transducer means in order to cause different frequencies in said waves to be advanced or delayed in time by different amounts, thereby to introduce time signal-processing into the output impulses. Preferred details are hereinafter set forth.

The invention will now be described with reference to the accompanying drawing, the single FIGURE of which is a combined longitudinal section and schematic circuit diagram of a preferred embodiment.

It has been determined that microwave elastic waves (phonons) can be converted into spin waves (magnons), and vice versa, by means of a spatially uniform but time-varying magnetic bias field in a single crystal yttrium iron garnet (YIG), as described in my article entitled "Phase-Velocity-Modulated Magnetoelastic Waves" appearing in the Journal of Applied Physics, Vol. 37, No. 8, July 1966, pages 3,326–7. Experiments have verified the theoretical prediction that such conversion occurs at constant wave number and momentum but with variable frequency, energy and power flux. Advantage is taken of this phenomenon, when modified in accordance with the present invention, to provide, among other things, a novel pulse compression or delay filter that is compact, versatile, affords greater compression ratios than conventional filter, and is suitable for wideband microwave radar systems and the like.

For purposes of illustration, the invention will be described in connection with its application as a chirp impulse compression filter. In its simplest form, the filter consists of a single crystal ferrimagnetic rod (such as YIG) capable of supporting elastic waves and provided with piezoelectric shear and longitudinal elastic wave transducers deposited respectively on the input and output end regions of the rod. A coil wound around the crystal is used to produce a transient or time-varying magnetic energy field bias. If the bias is a ramp function, turned on after an input electric chirp signal is introduced or coupled to the rod, it can serve to convert each frequency component of the input shear elastic wave, first to a magnetic spin wave and then to a longitudinal elastic wave of relatively fast velocity compared to the shear wave and of higher frequency that will couple to the output transducer. Because high-frequency components spend more transit time in the rod, proper choice of bias ramp will produce a matched filter output with noise factor improvement. In addition, and because of the frequency translation of the output impulse signal, the pulse compression factor is increased by a factor that is the ratio of the longitudinal to shear wave velocities V_l/V_s — normally a factor of about 2.

Such a filter is flexible because the bias current ramp can be altered to match a variety of chirp input impulses; and it is compact because for input pulses of microsecond duration, the crystal may be about 1 centimeter long. Such a filter is potentially wide band (within the limits of the transducers), moreover, because the linearity of the filter is as good as that of the bias ramp function. In principle, indeed, microsecond to nanosecond compression is possible. The peak bias energy required to filter one such pulse, furthermore, is typically a few millijoules.

Referring to the drawing, a preferred version of such a filter is shown in section comprising a sphere of polycrystalline YIG **1**, for example, diametrically cored and provided with a high quality single-crystal cylindrical rod **1'**, as of YIG, disposed within the core. Shear-wave (of the appropriate polarization) and longitudinal-wave electric-to-elastic wave transducers (such as CdS or ZnO) are deposited on the parallel and optically flat end faces at **2** and **4**, respectively. A solenoid coil **3** is wound about the sphere **1** such that the number of turns per unit length — as projected along the sphere axis — is a constant. The entire structure is magnetized to saturation either by a permanent magnet or an electromagnet. Current is passed through the coil **3** from a ramp generator **5**, the waveform being shown as the $I(t)$ vs. t graph, producing a substantially uniform spatial magnetic field inside of the sphere which adds a time-varying component to the bias field provided by magnet N–S. The chirped input pulse is applied to the shear-wave input transducer **2**, as schematically illustrated by the arrow INPUT, and, during such application, the time-varying ramp-controlled magnetic energy field produced by the solenoid coil **3** acts upon the system.

In operation, consider a frequency component ω entering the YIG rod **1'** via the input shear-wave transducer **2** from the chirp impulse at, say, time t. At a later time t_s, the current ramp from generator **5** will have produced a sufficient magnetic energy field in the solenoid **3** to cause conversion of the shear elastic wave to a spin wave. The component travels a distance V_s $(t_s - t)$ as a shear wave, and then stops (or propagates at a finite small velocity) for a further time interval $(t_1 - t_s)$ until longitudinal elastic-wave conversion occurs at time t_1. Finally, the component travels a distance V_l $(T - t_1)$ as a longitudinal elastic wave until exiting at the output transducer **4** at time T as an output signal-processed electric impulse, labelled OUTPUT.

For wave propagation parallel to the internal field (which, in turn, is parallel to the rod axis), the dispersion relation (ω vs k curve) has the form of a first rising curve, followed by a horizontal plateau, as disclosed in my said article, and then by a continuing or second rising curve. The plateau region can be moved up and down by varying the magnetic field at **5–3**, such that, in effect, the spin waves serve as a "magnon elevator," elevating the frequency ω from the first rising curve to the second curve where the frequency is thus increased, (or, on the removal of the ramp, causing the "magnon elevator" to drop back again or reverse). The final frequency that emerges at **4**, when the ramp has caused the magnon elevator thus to rise, is thus higher than the input frequency at **2** by the factor V_l/V_s, where, as before stated, V_l and V_s are respectively the longitudinal and shear-wave velocities. Since such higher frequency is delayed longer in the device, compression is effected by this frequency-changing (or velocity-changing) time signal processing. Power gain also results from this elevating or conversion action. The power handling capability, indeed, is inherently about 30 db greater than prior art magnetoelastic devices. The time signal-processing is effected, in accordance with the invention, by both the conversion between the types of elastic waves (through the spin-wave conversion) and by the differences in velocity therebetween.

Considering a one centimeter long YIG ferrimagnet magnetized in a "100" plane at 22.5° to the <100> axis or direction, a microsecond chirp pulse with ω variation from $2\pi\times10$to $3\pi\times10^9$ rad./sec., a relatively fast longitudinal wave velocity V_l of 7.2×10^5 cm./sec. directed along said direction, a slower shear-wave velocity of 3.9×10^5 cm./sec., 725 ampere turns in the solenoid coil 3, a ramp duration of 1.5×10^{-6} sec. for each successive input impulse, a magnetic field of the order of 400 oe./sec., and a peak energy delivered to the coil 3 of 1.3×10^{-3} joules, the following results are producible.

The critical time gradients for longitudinal wave conversion will range linearly with frequency from about 157 oe./μsec. at 1.85 GHz to 235 oe./μsec. at 2.77 GHz. The corresponding values of the conversion efficiencies range from 0.324 (−4.89 db) at 1.85 GHz, to 0.444 (−3.53 db) at 2.77 GHz. The average conversion loss for the signal pulse is approximately −4 db. In addition, there is a power gain of $(V_l/V_s)^2 = 3.4$ (+5.3 db), due to the frequency translation and change in group velocity. For this operation, the shear elastic wave transducer **2** should be flat over the frequency range 1–1.5 GHz; and the longitudinal transducer **4**, over the frequency range 1.85–2.77 GHz.

It has been found that at substantially the above-mentioned magnetizing angle of 22.5° to the "100" axis in the "100" plane, maximum interaction or splitting between the longitudinal and spin wave occurs in the YIG crystal. Up to about 26 percent improvement in such coupling and conversion has been determined as possible, moreover, for magnetizing and propagating the wave at an angle of substantially 25.52° to the "100" axis or direction in the "110" plane.

In summary, therefore, a novel and compact pulse compression filter employing elastic shear wave-spin wave/elastic longitudinal wave transduction by means of a time-varying magnetic field bias has been produced. The linearity of the filter is as good as the current ramp function can be made; and the bandwidth as wide as that of the input and output transducers. Sub-microsecond to microsecond input pulses can be accommodated. For 500 MHz. chirp bandwidths, compression into the nanosecond range is attainable. Compression is increased by the factor V_l/V_s over conventional filters. Another outstanding advantage is the ease and rapidity with which the filter may be matched to various input pulses by merely altering the bias waveform. The peak bias energy required to filter one pulse is typically a few millijoules; and while other ferrimagnetic and similar devices may be used, the single crystal YIG appears to be a most suitable device for these purposes. While the spatial gradient of the magnetic field has been described as uniform, moreover, it may also be varied or non-uniform along the crystal device; and other fields besides magnetic fields may, in certain instances, be employed to create the non-uniform time-varying conversion process.

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. An electric-impulse signal-processing apparatus having, in combination, an elastic-wave-supporting device, input and output transducer means disposed at the device for respectively coupling electric impulses thereto to generate and propagate elastic waves therein and for transducing such waves into electric output impulses, and means for applying a transient time-varying energy field to the device during the coupling of said electric impulses into the device by the input transducer means, and which varies substantially during the transit of an impulse in said device, in order to cause different frequencies in said waves to be advanced or delayed in time by different amounts, thereby to introduce time signal-processing into the output impulses.

2. An electric-impulse signal-processing apparatus as claimed in claim **1** and in which said field is magnetic and means is provided for converting said elastic waves to spin waves upon which the time-varying energy field acts in the manner of a magnon elevator.

3. An electric-impulse signal-processing apparatus as claimed in claim **2** and in which means is provided for converting said spin waves to elastic waves for transducing into said electric output impulses.

4. An electric-impulse signal-processing apparatus as claimed in claim **2** and in which the time-varying field is applied and removed to cause the magnon elevator action to reverse.

5. An electric-impulse signal-processing apparatus having, in combination, an elastic-wave-supporting device capable of supporting relatively slow and fast elastic waves, input and output transducer means disposed at the device for respectively coupling electric impulses thereto in order to generate and propagate therein one of the said elastic waves and for transducing the other of said elastic waves into electric output impulses, and means for applying a transient time-varying energy field to the device during the coupling of said electric impulses into the device by the input transducer means, and which varies substantially during the transit of an impulse in said device, in order to cause the said one elastic waves propagating in said device to become converted into the said other elastic waves, thereby to introduce time signal-processing into the output impulses caused both by the conversion from the said one to the said other elastic waves and by the difference in velocity therebetween.

6. An apparatus as claimed in claim **5** and in which said device comprises magnetic crystal means and said time-varying energy field is produced by time-varying magnetic field-producing means.

7. An apparatus as claimed in claim **6** and in which said crystal means comprises a YIG crystal and said transducer means comprise shear and longitudinal elastic-wave transducers.

8. An apparatus as claimed in claim **7** and in which the said YIG crystal is a single rod disposed within an outer polycrystal YIG structure about which the magnetic field-producing means is disposed.

9. An apparatus as claimed in claim **8** and in which the outer YIG structure is substantially spherical and the said YIG crystal is disposed substantially diametrically therein.

10. An apparatus as claimed in claim **5** and in which the said electric impulses comprise a frequency-modulated pulse, the said one and other elastic waves are respectively the said slow and fast waves, and the said signal processing results in compression of the input electric impulses.

11. An apparatus as claimed in claim **6** and in which the said magnetic field is oriented relative to said crystal means in one of a substantially 22.5° angle to the "100" axis in the "100" plane and a substantially 25.52° angle to the "100" axis in the "110" plane.

12. Apparatus as claimed in claim **2** and in which means is provided for spatially varying field along the device.

13. An electric-impulse signal-processing apparatus comprising a magnetic crystal including YIG, and a magnetic-field-producing means oriented to set up its field at one of a substantially 22.5° and a 25.52° angle with respect to the "100" axis in the respective "100" and "110" planes.

14. Apparatus as claimed in claim **13** and in which means is provided for propagating elastic waves in said crystal substantially along said "100" axis.

15. A method of changing the transit time of relatively low and high frequency components of elastic impulses, that comprises, propagating such impulses in an elastic-wave-supporting medium, and, during the propagating, subjecting the medium to a transient time-varying energy field apart from said impulses which varies substantially during the transit of an impulse in said medium.

16. A method as claimed in claim **15** and in which said field is magnetic and said propagating comprises introducing one type of elastic wave into said medium and converting the same to a spin wave therein upon which the time-varying energy field acts in the manner of a magnon elevator.

17. A method as claimed in claim **16** and in which the spin wave conversion is followed by conversion into a second type of elastic wave.

18. A method as claimed in claim **17** and in which the said types are relatively slow and fast elastic waves.

19. A method as claimed in claim **16** and in which there is further effected spatial varying of field along the medium.

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