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Morgenthaler

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[54] AN ARTICLE FOR PROCESSING ELECTROMAGNETIC WAVE ENERGY

[75] Inventor: **Frederic R. Morgenthaler,** Wellesley Hills, Mass.

[73] Assignee: **Massachusetts Institute of Technology,** Cambridge, Mass.

[22] Filed: **Aug. 23, 1971**

[21] Appl. No.: **173,884**

Related U.S. Application Data

[63] Continuation-in-part of Ser. Nos. 645,947, June 14, 1967, Pat. No. 3,530,302, and Ser. No. 740,751, June 27, 1968, Pat. No. 3,609,596.

[52] **U.S. Cl.** **117/234,** 307/88.3
[51] **Int. Cl.** **H01f 10/02**
[58] **Field of Search** 117/234, 235, 239, 237; 252/62.57, 62.58; 307/88.3

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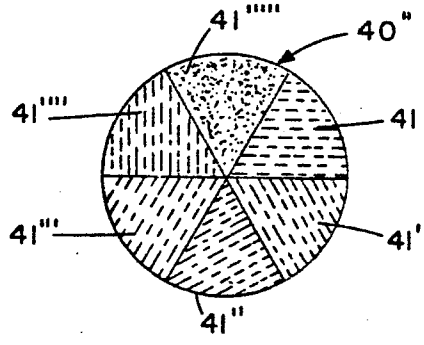
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Primary Examiner—Michael Sofocleous
Assistant Examiner—Bernard D. Pianalto
Attorney, Agent, or Firm—Arthur A. Smith, Jr.; Robert Shaw; Martin Santa

[57] **ABSTRACT**

A device for processing electromagnetic wave energy by converting the wave energy to spin waves and/or elastic waves, the present disclosure being particularly directed to the concept of providing a device made up of a single-crystal material which contains non-uniform material parameters to give graded values of material saturation $4\pi M_s$. The material discussed in greatest detail is YIG and the non-uniform material parameters are furnished by doping the YIG with gallium. The graded material parameters in combination with an external magnetic bias field $\bar{H}$ result in an internal magnetic bias field H. The electromagnetic energy as it enters the material is acted upon in a manner that is influenced greatly by the contour of H. The contour of H in the present disclosure, in turn, is predetermined to present gradations in H which will allow the conversion mentioned and which allow predetermination of the wavenumber k of the magnons and/or phonons thereby formed. Furthermore, the place or space within the crystal at which conversion occurs can be somewhat determined by the profile of H thereby provided.

10 Claims, 12 Drawing Figures



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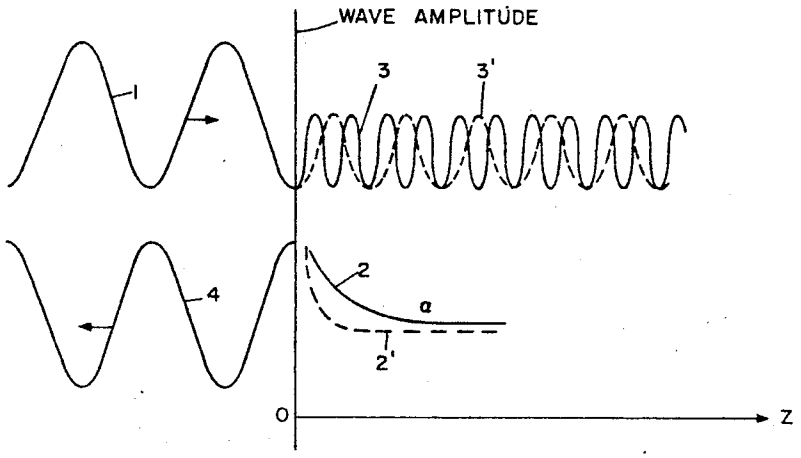


FIG. 1

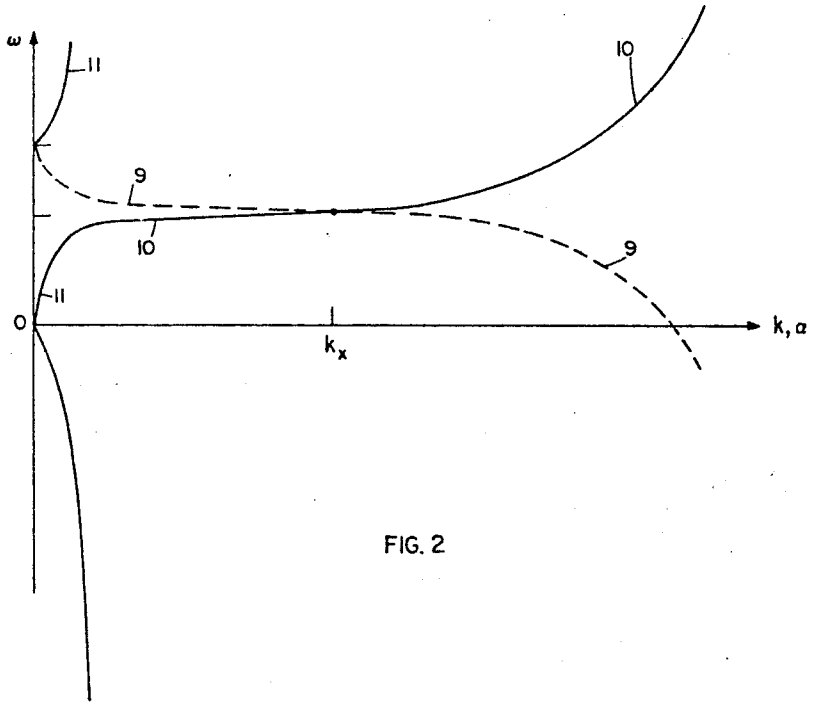


FIG. 2

INVENTOR:
FREDERIC R. MORGENTHALER
BY
ATTORNEY

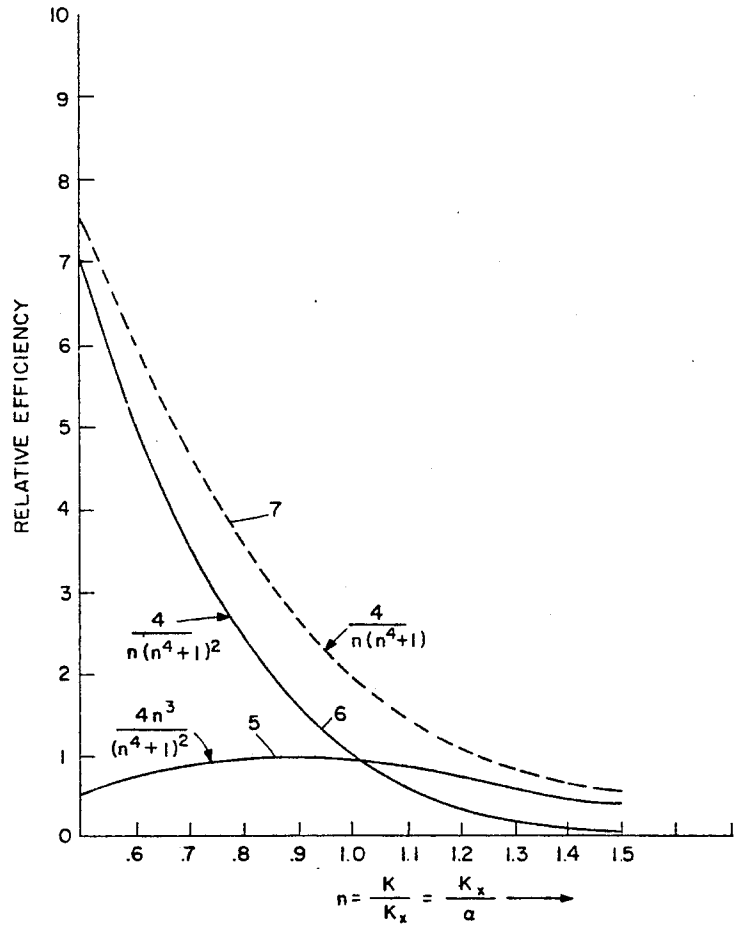


FIG. 3

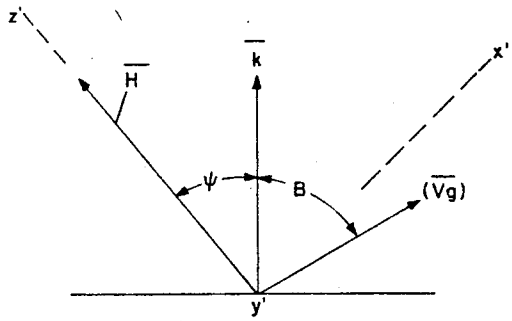


FIG. 4B

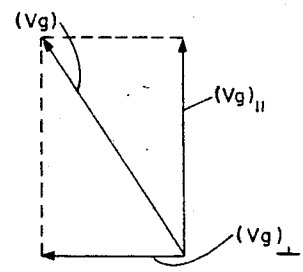


FIG. 4A

INVENTOR:
FREDERIC R MORGENTHALER
BY
ATTORNEY

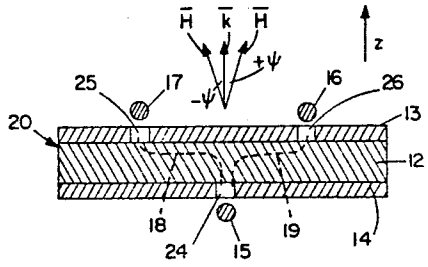


FIG. 5

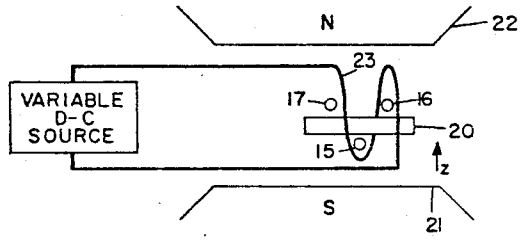


FIG. 6

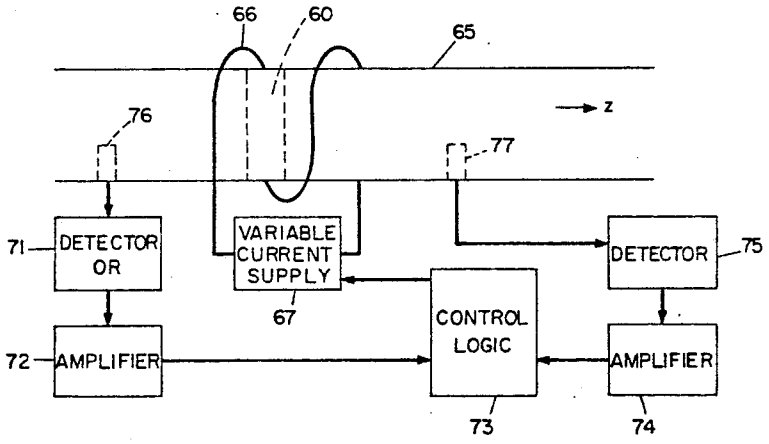


FIG. 7

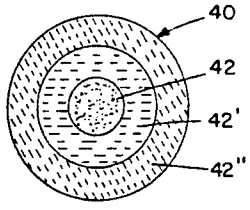


FIG. 8

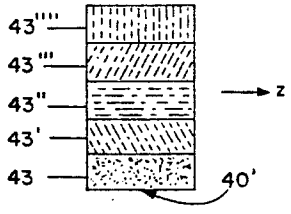


FIG. 9

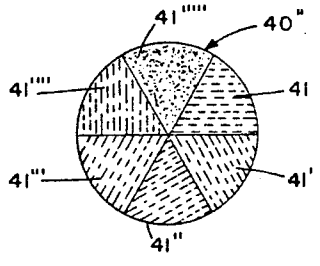


FIG. 10

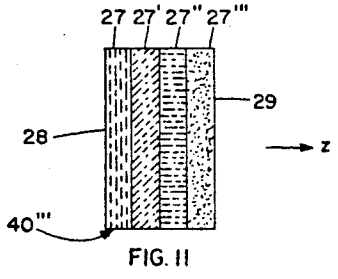


FIG. 11

INVENTOR:
FREDERIC R. MORGENTHALER
BY
ATTORNEY

ARTICLE FOR PROCESSING ELECTROMAGNETIC WAVE ENERGY

The invention herein described was made in the course of contracts with the Office of the Secretary of Defense, Advanced Research Projects Agency, and Air Force Cambridge Research Laboratories, Office of Aerospace Research.

This application is a continuation-in-part of application Ser. No. 645,947 filed June 14, 1967 (now U.S. Pat. No. 3,530,302) and application Ser. No. 740,751, filed June 27, 1968 (now U.S. Pat. No. 3,609,596), and is being filed in response to a requirement for restriction in each instance.

In an application for Letters Patent entitled, "Method of and Apparatus for Changing Frequency, Power and/or Delay Time of Wave Energy," Ser. No. 645,947, filed June 14, 1967 by the present inventor (now U.S. Pat. No. 3,530,302), there is described apparatus and method for converting electromagnetic wave energy to propagating spin wave and/or elastic wave energy and vice versa. It is noted therein that under appropriate circumstances the conversion from one to the other form of energy can be made and the angular frequency (ω) and wavenumber (k) of certain propagating wave energy can be changed by changing the environmental parameters within the material. In an article entitled, "Photon/Magnon Conversion Near A Material Interface," in *Electronics Letters*, July 1967, Vol. 3, No. 7, pp. 299–302, the present inventor discusses delay means whereby substantial time delay of wave energy is obtained even in thin film materials and in a relatively non-dispersive fashion. Thus, it has been found that under appropriate circumstances an electromagnetic wave propagating in air may be presented, for example, to a magnetic material and can be converted to evanescent wave energy and propagating spin wave energy within the material. Whereas the spin wave propagates within the material, the evanescent wave is stationary and degenerates asymptotically spatially, there being an interchange of energy between the evanescent wave and the propagating wave which results in evanescent wave energy being transferred to the propagating spin wave and vice versa.

The apparatus hereinafter described is adapted to provide time delay of electromagnetic wave energy; but, in addition, it provides filtration and/or switching as well. It has been found, moreover, for present purposes, that although there can be no conversion at the interface boundary from electromagnetic power transfer in air to quantum mechanical exchange power transfer by the propagating spin wave in the material, nevertheless, under certain conditions, conversion can occur near the boundary. Conversion from conventional electromagnetic wave energy to spin wave energy, as noted in U.S. Pat. No. 3,530,302, may be effected by presenting a graded internal magnetic bias field to the electromagnetic wave or by adjusting the level of the bias field to one at which conversion can take place. In the present case a delay material is chosen that is adapted to present an abrupt discontinuity to the electromagnetic wave energy, thereby to provide photon-to-magnon conversion very near the material interface, the level of the external magnetic bias field being adjusted to an appropriate level to effect such conversion. The direction of propagation of the spin wave and the direction along which the evanescent wave degenerates is determined, as hereinafter discussed in greater detail, by the direction of the incoming wave into the magnetic material and the direction and magnitude of the internal d-c magnetic bias field. It is also possible, using the principles taught herein, to control the direction of spin wave power flow in the material and to change that direction very quickly by, for example, small changes in the d-c bias field. Accordingly, a principal object of the present invention is to provide apparatus and method adapted to switch a microwave electromagnetic signal from, for example, one output to another in microseconds by providing magnetic apparatus that is very sensitive to changes in the direction and magnitude of an internal d-c magnetic field, provision being made for changing the magnitude and/or direction of the field.

It has been found that if the wavenumber of the spin wave at conversion is at a value herein designated k_x in the $\omega - k$ diagram, there is a maximum transfer from evanescent wave energy to spin wave energy, and, at that value, approximately 50 percent of the spin wave power is carried in each of the electromagnetic channels and the quantum mechanical exchange channels. Also, k_x represents the value at which the group velocity of the propagating spin wave, in the absence of transverse boundaries, is minimum so that delay is maximized and at which dispersion is also minimum so that the integrity of the input wave is maintained. Therefore, the delay material is chosen, and the external magnetic bias is adjusted to provide an appropriate environment to effect conversion near the interface at values of wavenumber k which result in the desired delay and allowable dispersion for the particular application. Hence, another object of the present invention is to provide a method of and apparatus for providing substantial time delay of electromagnetic wave energy while nevertheless preserving substantially the wave shape of the input energy.

A further object is to provide such substantial time delay even in a thin film material.

Another object is to provide a delay means for electromagnetic wave energy in which the energy is subjected to one or more abrupt discontinuities by providing a magnetic material consisting of one or more layers or regions to provide the discontinuities.

In delay apparatus for which the present invention is adapted, it is important not only that an appreciable delay time be provided in a small volume; but it is also of importance that the delay time, once established, be substantially constant. Since, in equipment, the environmental parameters presented to the wave energy will change due, for example, to temperature changes, electric current fluctuation to the coils that provide the external bias field, and the like, it is to be expected that changes in delay time of the wave energy will occur; accordingly, an additional object of the present invention is to provide ways for reducing the effect upon delay time of uncontrollable changes in the equipment.

A still further object is to provide apparatus in which the time delay of the wave energy is related to the magnetic field thereby to give an indication of the magnitude of the magnetic field.

Another object is to provide apparatus adapted to remove or filter undesirable frequencies of the wave energy.

Other and further objects will become evident in the specification to follow and will be more particularly pointed out in the appended claims.

The objects of the invention are attained, broadly, by a method that comprises, introducing electromagnetic wave energy to a material that will support propagating spin wave energy and evanescent wave energy and allow interchange of energy therebetween, the material being one in which the electromagnetic wave energy can be converted to evanescent wave energy and propagating spin wave energy and in which the group velocity of the propagating wave and the rate of decay of the evanescent wave can be varied by varying the environmental parameters within the material. The material parameters are such that, when subjected to an appropriate applied magnetic field, an abrupt discontinuity is encountered by the electromagnetic wave thereby to effect the conversion of the wave energy from electromagnetic power to a combination of evanescent and spin wave, the spin wave power being carried in the electromagnetic channel, the quantum mechanical exchange channel or a combination thereof.

The invention will now be explained in connection with the accompanying drawings in which:

FIG. 1 is a sketch representing a wave amplitude profile showing input and reflected electromagnetic wave energy at an airmaterial interface of a magnetic material and evanescent and spin wave energy within the material;

FIG. 2 is a sketch representing the intrinsic relationship between angular frequency (ω) and wavenumber (k) of the spin wave and decay rate (α) of the evanescent wave in the material in the absence of transverse boundaries and for the special case in which the angle ψ defined below equals zero and the wave energy is circularly polarized;

FIG. 3 is a graph of the relative conversion efficiency of power from electromagnetic wave energy in air to electromagnetic spin wave energy and exchange spin wave energy in the magnetic material as a function of n, where $n = k/k_x = k_x/\alpha$ and where k_x is a point on the $\omega - k$ and $\omega - \alpha$ curves in FIG. 2 at which $k = \alpha$;

FIG. 4A is a vector diagram to show the group velocity (V_g) of a spin wave as a vector sum of the parallel component $(V_g)_{\parallel}$ and the perpendicular component $(V_g)_{\perp}$;

FIG. 4B shows the vector relationship between the wave vector $\bar{k}$ and the group velocity vector ($\bar{V}_g$), when there is some angle ψ between $\bar{k}$ and an internal magnetic field designated $\bar{H}$, and cartesian coordinates x', y', z' are also shown;

FIG. 5 is a cross sectional view of a magnetic material adapted to perform the functions herein disclosed;

FIG. 6 shows the material of FIG. 5 in reduced size and also, schematically, shows means for providing a z-directed internal d-c magnetic field with further means for rotating the field through angles $+\psi$ and $-\psi$ to the z-direction;

FIG. 7 is a modification of the apparatus of FIG. 5 and shows a magnetic material within a waveguide; and

FIGS. 8, 9, 10 and 11 show some variations of the magnetic material shown in FIG. 7.

Turning now to the drawings, apparatus is shown generally at 20 in FIGS. 5 and 6 for providing time delay, frequency selectivity and switching of electromagnetic wave energy. The apparatus comprises a magnetic material 12 (which may be a single crystal doped yttrium iron garnet [YIG]) in the disclosed embodiment with a first non-magnetic metal reflection wall 14 (which may be a thin film of silver, aluminum, gold or the like) secured to one face thereof and a second metal reflection wall 13 secured to the other face. An input aperture or window 24 admits electromagnetic energy to one region of the magnetic material 12 and output apertures or windows 25 and 26 allow the energy to be withdrawn from the material at another region thereof. Output apertures other than 25 and 26 may be provided, and the relative lateral positions of 24, 25 and 26 may be changed, the wave energy being directed to one or the other of the windows in a manner explained hereinafter. The material is one that will support propagating spin wave energy and evanescent wave energy; and is, further, one in which the electromagnetic wave energy can be converted to evanescent and spin wave energy and which allows interchange of energy between the evanescent wave and the spin wave. In addition, the group velocity (V_g) (the path of travel of power in the spin wave, as represented by either of dotted lines 18 and 19 in FIG. 5, is the same direction as the group velocity vector) of the spin wave and the rate of decay (α) of the evanescent wave can be varied by varying the environmental parameters within said material. A suitably doped yttrium iron garnet crystal serves the foregoing purposes. The material parameters of YIG can be varied by different types and amounts of dopant (See an article entitled, "Magnetic Effects of Indium and Gallium Substitutions in Yttrium Iron Garnet," Anderson et al., *Journal of the Physical Society of Japan*, Vol. 17, Supplement B–1, Proceedings of the Conference on Magnetism and Crystallography, September 1961), and the material parameters in combination with an external applied d-c magnetic field compose the environmental parameters (i.e., the internal d-c magnetic bias field) encountered by the wave energy within the material. The value of the magnetic field and the magnetic characteristics of the particular material used are chosen to provide at least one abrupt discontinuity in the equilibrium environmental parameters to effect the conversion from electromagnetic power to a combination of evanescent and propagating spin waves, the spin wave power being carried in the electromagnetic channel, the quantum mechanical exchange channel or a combination thereof.

It is in order now to discuss the theory of the concepts herein disclosed. The discussion in the Morgenthaler article relates to the special case of a positively circularly polarized electromagnetic wave in air at normal incidence to the interface boundary between air and a lossless material, as a lossless material 12. In the special case the angles ψ and β discussed below both equal zero. The discussion to follow, however, relates to the general case where ψ and β need not equal zero and, in fact, cannot equal zero if steering of the propagating spin wave is to be effected. The angle β, as shown in FIG. 4B, is the angle between the $\bar{k}$ vector of a spin wave and the group velocity vector designated ($\bar{V}_g$) when the internal bias field H_z is at some angle ψ to the $\bar{k}$ vector. A number of expressions may be used to define the angle β, as discussed later, one such expression being the following:

$$\tan \beta \approx \frac{1}{2+\frac{\omega_M \sin^2 \Psi}{\omega_s + \lambda k^2 \omega_M}} \cdot \frac{\sin 2\Psi}{2\lambda k^2} \qquad (1)$$

where k is the wavenumber of the propagating spin wave; λ is the exchange constant (approximately 3×10^{-12} cm^2 for YIG); ω_M is a constant ($\approx \pi \times 10^{10}$ rad/sec for YIG); $\omega_z = |\gamma| \mu_o H_z$, where γ is the gyromagnetic ratio and μ_o is the permeability of free space ($\omega_z \approx 2\pi \times 2.8 \times 10^6 \times H_z$ (oe.) rad/sec for YIG); $k_o = \omega/c$, where c is the velocity of light and equals 3×10^{10} cm./sec. and $\omega \approx \omega_z$. The expression shown at (1) does not include magnetic anisotropy and is valid if $\lambda k^2 >> k_o^2/k^2$. The following expression is valid if $\psi << 1$ and $k >> k_o$:

$$\tan \beta \approx \psi/2 \, (\lambda k^2 + [k_o^2/k^2]) \tag{2}$$

The expression (2) includes higher order corrections to the magnetostatic approximation and, again, does not include magnetic anisotropy. The exact expression for tan β has the property that as $k \rightarrow k_o$, $\beta \rightarrow o$ independent of ψ.

The following analysis (expressions (3) through (9)) is carried out in the magnetostatic approximation, is valid when magnetic anisotropy is present and approaches the exact solution for large values of k, i.e., $k >> k_o$:

$$\langle \bar{e}_1 \times \bar{h}_o \rangle = (\omega \mu_o a^2 \sin 2\psi/4k^2) \cdot (\bar{i}_y' \times \bar{k}) \tag{3}$$

$$\bar{m}_o = \bar{i}_x' \, a \cos(\omega t - \bar{k} \cdot \bar{r}) + \bar{i}_y' \cdot b \sin(\omega t - \bar{k} \cdot \bar{r}) \tag{4}$$

$$\langle -\mu_o \lambda (\delta \bar{m}_o/\delta \bar{r}) \cdot (\delta \bar{m}_o/\delta t) \rangle = \mu_o \delta \omega \bar{k} \, [(a^2 + b^2)/2] \tag{5}$$

$$\langle W \rangle = \tfrac{1}{2} \mu_o (ab/\omega_M) \omega \tag{6}$$

$$\langle \bar{s} \rangle = \langle \bar{e}_1 \times \bar{h}_o \rangle + \langle -\mu_o \delta (\delta \bar{m}_o/\delta \bar{r}) \cdot (\delta \bar{m}_o/\delta t) \rangle = \langle W \rangle \bar{V}_g \tag{7}$$

$$(\bar{V}_g) = (\bar{V}_g)_{\parallel} + (\bar{V}_g)_{\perp} = [(a^2 + b^2)/ab] \, \delta \omega_M \bar{k} + (a/b)(\sin 2\psi/2)(\omega_M/k^2)(\bar{i}_y' \times \bar{k}) \tag{8}$$

$$\tan \beta = (\bar{V})_{\perp} / (V)_{\parallel} = [a^2/(a^2 + b^2)](\sin 2\psi/2 \lambda k^2) \tag{9}$$

where $\langle \bar{e}_1 \times \bar{h}_o \rangle$ is the time-averaged electromagnetic power flux (watts/m^2), $\bar{e}_1$ is the electric field (volts/m), $\bar{h}_o$ is the magnetic field (amperes/m.), a and b are the amplitudes of the small signal (s.s.) magnetization vector m_o (amperes/m.) ($a = b$ in a circularly polarized wave and $a \neq b$ in an elliptically polarized wave), $\bar{i}_x'$ and $\bar{i}_y'$ are unit vectors in cartesian coordinates, $\bar{r}' = \bar{i}_x' x' + \bar{i}_y' y' + \bar{i}_z' z'$, t is time (seconds), $\langle -\mu_o \lambda (\delta \bar{m}/\delta \bar{r}) \cdot \delta \bar{m}/\delta t \rangle$ is the quantum mechanical exchange power flux (watts/m^2), $\langle W \rangle$ is the time-averaged energy density of the wave (joules/m^3), ω_M is $|\gamma| \mu_o M_s$, M_s is the saturation magnetization (amperes/m), $\langle \bar{s} \rangle$ total time average power flux (watts/m^2), and $(V_g)_{\parallel}$ and $(V_g)_{\perp}$ are respectively the components of $(\bar{V}_g)$ parallel and perpendicular to the k vector. From the foregoing expressions it can be seen that the path (**18** or **19**, for example, in FIG. **5**) taken by the propagating spin wave within the material **12** can be changed in a number of ways. It is possible to perform a switching function by, for example, tilting the H field from $+\psi$ to $-\psi$ in FIGS. **5** and **6** to switch the output from the window **25** to the window **26** (a z-directed field in FIG. **6** can be provided by poles **21** and **22** and changes from $+\psi$ to $-\psi$ can be effected by the coil shown schematically at **23**), or the external bias field can be changed in magnitude to effect changes in β. Furthermore, as will be explained more fully hereinafter, the delay time of the wave energy within the material **12** can be varied by changing the internal bias H in magnitude and/or direction, and the frequencies that will reach the ports **25** and **26** along paths **18** and **19**, respectively, can be affected in like manner to accomplish a filtering function. However, before any work can be performed upon a spin wave, a spin wave must be created. The more general explanation of conversion from electromagnetic power to spin wave power contained in said U.S. Pat. No. 3,530,302 is summarized below and amplified in some particulars. The circuit arrangement to provide the results discussed can be that shown in FIG. **7**, where a magnetic material **60** is shown disposed within a waveguide **65**.

A profile representation of the wave energy previously discussed may be that shown in FIG. **1**, where **1** represents incoming electromagnetic wave energy traveling in air, which enters a material and converts to evanescent wave energy (the decay rate of which is represented by the curve shown at **2**) and propagating spin wave energy (represented by the sinusoid shown at **3**). (In FIG. **1**, at the air side of the interface, in addition to the incoming wave **1**, there is shown a similar but oppositely directed wave **4** to represent reflected electromagnetic energy.)

The ordinate in FIG. **1** can be taken as an interface representing, for example, air to the left and some magnetic material **60**, as yttrium iron garnet or other material to the right. It is pointed out in the Morgenthaler article that when the wavenumber k of the spin wave during conversion is equal to some value k_x in FIG. **2** ($n = k/k_x = 1$), the group velocity of the spin wave is minimum, resulting in greatest delay time in the material; and, also, dispersion is minimum. Moreover, at k_x the curves $\omega - k$ and $\omega - \alpha$ coincide.

Some of the electromagnetic energy represented by the curve **1**, upon entering the delay material, proceeds axially (in the z direction) within the material and through. This represents a small amount of the input energy, and it passes along out of the material, with some delay time. It is propagating wave energy and may be termed a precursor because it serves the useful function of preceding the energy to come behind and begins the establishment of the evanescent wave. At or near the interface an evanescent wave forms which decays in magnitude, as represented by the curve **2**. The rate of decay α can be modified, for example, by changing the internal magnetic bias H, to the value shown, for example, at **2'**; the particular condition depicted by **2'** results from an increase in the internal magnetic bias field H. (The change in H may be effected by changing the strength of the external field or by providing appropriate material gradations by doping the YIG material, as discussed in the Anderson et al. article.) In FIG. **2** the $\omega - k$ curves shown at **10** and **11**, representing spin waves and electromagnetic waves, respectively, and the $\omega - \alpha$ curve shown at **9** of the evanescent wave will all shift upward as a result of the increase in H, and k_x would shift to the right of the position shown, the shift reflecting the increase in decay rate α, represented by the curve **2'**, and the increase in wavenumber k, represented by the dotted curve shown at **3'**. An appropriate value of external magnetic bias can be applied, therefore, to give the desired point of conversion to fit a particular requirement.

A more complete explanation of the method of power transfer in the spin wave will now be made. The

discussion is restricted to a situation wherein a circularly polarized electromagnetic wave in air is introduced to a delay material at the air-to-material interface and the wave, upon striking the face, does so along a line that is orthogonal to said face; i.e., the direction of propagation is axial (z-directed in FIG. 7) and the faces of the delay material, as the material 60, are perpendicular to said direction. Furthermore, a z-directed external d-c magnetic bias field of sufficient magnitude to saturate the material is used. In such a circumstance the group velocity of the spin wave (V_g) is equal to the parallel component $(V_g)_{\|}$ thereof, but (V_g) does not equal $(V_g)_{\|}$ except in this special case.

Spin waves refer to energy waves appearing in a material by virtue of precessional movement of electrons about a magnetic axis. Energy can be pumped into the spin wave or removed therefrom. The dipoles formed by the precessional movement pass energy to adjacent dipoles by quantum mechanical exchange means or by electromagnetic means. Either way, however, the frequency of the wave bears a one-to-one relationship with the precessional movement of the dipoles, and, indeed, there is at all times some electromagnetic power transfer mixed with some exchange power transfer within the spin wave. Since electromagnetic power tends to travel fast, at the speed of light in air but at reduced speed in magnetic materials, and the exchange power travels relatively very much slower, the speed at which power transfer takes place within the material depends upon the relative mixture of the forms of power appearing in the spin wave. At values of $n < 1$, the conversion of power to the electromagnetic spin wave channel, as shown by the curve shown at 6 in FIG. 3, is much greater than the conversion to the quantum mechanical exchange channel of the spin wave, as represented by the curve shown at 5. (The combined efficiency is represented by the curve shown at 7.) The parallel component as a function of n is $(V_g)_{\|} \sim [(n^4 + 1)/2n^3]$ and rises dramatically for values of $n < 1$. (The perpendicular component, though not being considered at this juncture, is also a function of n, in the magnetostatic approximation, bearing the relationship $(V_g)_{\perp} \sim 1/n$.) Thus the values of k and α at which conversion takes place to spin wave determines the ratio of power being carried in the electromagnetic channel and the quantum mechanical exchange channel in the resultant propagating wave at that point and the group velocity of the spin wave.

The explanation in the previous paragraph, as mentioned, was made on the basis that the incicent electromagnetic wave is positively circularly polarized and introduced to a ferromagnetic or other appropriate material, having a pair of flat parallel faces, along a direction of propagation perpendicular to said faces, i.e., in the z direction. In addition, the internal magnetic bias H in the material is parallel to the direction of propagation, and the material is magnetized to saturation. If, however, the incident wave is not so directed or if the magnetic bias is directed in some direction other than z, then ψ will change and according to expressions (2) and (9) can vary radically from the previous value. For example, for $k_o = 1$ cm.$^{-1}$, $k = 50$ cm.$^{-1}$, $\lambda k^2 << k_o^2/k^2$ and the expression (2) becomes: $\tan \beta \approx 1{,}250\ \psi$, where ψ is in radians. A change of ψ from zero to 1° will alter β from zero to approximately 87°. Also, for any given material at a given magnetic bias, the spatial conversion from electromagnetic power can be altered by varying the angle of incidence to some other value, and in such circumstances k and α respectively of the propagating and evanescent spin waves will change from the particular value obtained using the z-directed wave. It should be noted, however, that when the angle of incidence and/or d-c field direction are altered, the simple conditions discussed in the Morgenthaler article do not apply; in particular, spin waves having both an $\bar{\alpha}$ and $\bar{k}$ (even in the lossless case) can occur under some conditions and be excited at the interface. Such surface waves have the property that power is guided along or at an angle to the surface and, like the simpler waves, can provide useful functions, such as delay, switching and/or filtering. The effect on power flow due to departures from the special case can be seen upon reference to the mathematical expression previously presented.

Thus, a switch for microwave electromagnetic energy can be made using the principles herein disclosed, and such a switch is capable of effecting switching from one output to another, as outputs 25 and 26 in FIG. 5, very quickly (of the order of microseconds) with milli-watts of power required to effect such switching. The input electromagnetic energy can be introduced to the single crystal YIG material 12 at the input port 24 through a conductor 15 and removed through either of output conductors 16 and 17 at output ports 26 and 25, respectively, switching the path of power travel within the material 12 being effected by changing the direction of $\bar{H}$ from $+\psi$ to $-\psi$, as before discussed. An ambient magnetic field between the pole piece 21 and 22 of an electromagnet is provided at a level to establish a magnitude of internal bias H at which conversion from electromagnetic power transfer to spin wave power transfer can occur, as previously mentioned. The level of H thereby established is such that the wavenumber k of the propagating spin wave is substantially greater than k_o to enable the low-power, short-time switching just mentioned. For, as before discussed, as $k \rightarrow k_o, \beta \rightarrow o$, independent of ψ, so that the apparatus herein disclosed cannot be used at very low k values, i.e., much below about $5k_o$.

The discussion in the previous paragraph relates to the switch function of the present invention which may also serve as a computer memory element. It will be noted, however, that wave energy at different frequencies will be converted to spin waves having different k/k_o ratios; therefore, according to expressions (2) and (9) the angle β is a function of frequency. Thus, with reference to FIG. 5, energy entering at the port 24 may, for example, pass along the path 18 to be removed at the output port 25. However, only a narrow band of frequencies will be removed at 25 because the angle β for each narrow band will differ from the angle β of each other narrow band.

In order to determine and control time delay of electromagnetic energy introduced to pass from left to right in the waveguide 65 in FIG. 7, a probe 76 can be provided within the waveguide to pick up the incoming signal, which may be in the form of a series of pulses, and the time delay effected by the material 60 can be determined by relating the incoming pickup by the probe 76 to an outgoing pickup by a probe 77. The amount of delay can be modified by feeding the signals from the two probes to a variable d-c current supply 67 thereby to modify the current in the coil 66 to render changes in H, as before discussed. The signals from the probes 76 and 77 are passed through detectors 71 and 75, re-

spectively; and the detected signals are then amplified by amplifiers **72** and **74**, the outputs of which are fed to a control logic device **73** and thence to the current source **67**.

It is possible, therefore, by using a suitable magnetic material and appropriate bias, to achieve a condition where conversion can take place. Thus, a YIG rod with suitable dopant added can be biased to a value at which conversion can take place; and the level of internal magnetization can be chosen to provide conversion from electromagnetic energy to spin wave energy with no provision for the elastic wave or for conversion of the elastic wave energy, as discussed hereinafter. In order to effect conversion at a desired region in the material, the composite materials shown at **40**, **40'**, **40''** and **40'''** of FIGS. **8**, **9**, **10** and **11**, respectively, may be used in the waveguide arrangement of FIG. **7**. (The *z* direction in FIGS. **8** and **10** is out of the paper or into the paper, whereas the *z* direction in FIGS. **9** and **11**, as shown, is to the right.) The composite materials are provided by varying the dopant in different regions of the crystal. Thus, for example, radially disposed regions **42**, **42'** and **42''** of the crystal **40** are doped in such a fashion that at a given applied field the internal magnetic bias of the film **40** will vary from region to region. Similar remarks apply to multi-transverse layers **43**, **43'**, etc., of FIG. **9**, the wedge-shaped regions **41**, **41'**, etc., of FIG. **10** and the multi-axial layers **27**, **27'**, etc., of **40'''**. Thus, a *z*-directed wave incident upon the delay material of FIG. **7** will encounter—if crystals similar to **40**, **40'** and **40''** are used—a plurality of transversely disposed regions in which the environmental parameters vary from region to region and conversion from electromagnetic energy to propagating spin wave energy will occur in that region wherein the environmental parameters are at an appropriate level for such conversion. Furthermore, the composite crystal **40'''** of FIG. **11** can include layers of the type disclosed in FIGS. **8**, **9** and **10**.

A further benefit may be derived from a magnetic material having graded material parameters. Assume, for example, that the material is graded so that a uniform external *z*-directed magnetic field results in an internal bias H which is maximum at the center of the film and decreases transversely toward the outside edges thereof; that is, with reference to FIG. **8**, the region **42** has maximum *z*-directed H values and **42'** and **42''** have respectively lesser values of H at one value of uniform applied field. Then electromagnetic energy into the material in FIG. **7** is converted in the manner previously discussed and will be withdrawn after a time delay. The length of time delay will depend to a great extent upon the point of conversion within the film. Energy passing through the region **42** will convert at a different point along the path of travel than energy in the region **42'**, which will, in turn, differ from energy in **42''**. If the gradations vary uniformly from the center outward, for example, then there will be dispersion of the energy in the material. However, pulses, for example, will have quite uniform time delay and dispersion, even with changes in the magnitude of internal bias H, since the effect of such changes will be merely to shift the region through which wave energy of any particular group velocity will travel; and the resultant output pulse formed from the various group velocities involved will not change appreciably, being effectively a total which will not be affected as a whole to the extent that the individual components thereof are affected. Furthermore, the point of conversion will have an effect on the switching and filtering functions previously discussed.

The external magnetic field provided by the coil **66** should ideally be uniform throughout the region occupied by the magnetic material. However, even if such uniformity exists, the internal bias field H will tend to be lower near the faces thereof, as the faces shown at **28** and **29** in FIG. **11**, than within the interior thereof because of demagnetization due to dipole effects. For this reason, it is often desirable to provide a multi-layer material as, for example, the multi-layer device **40'''** in which the dopant and amounts of dopant differ from layer to layer to counteract to some extent the dipole effect and also to provide the abrupt discontinuity as a series of smaller discontinuities. Thus, the material **40'''** can be used to provide a particular profile of internal bias H in the *z* direction and can be used, for example, to overcome to some extent the demagnetizing effect of dipole action. Furthermore, whereas changes in effective internal field strength, effected by changes in the external field or by effectively reducing the distance between field lines, are completely governed by Maxwell's equations, similar changes effected by modifying the dopant are not so governed, insofar as the magnetic anisotropy is involved. Even without anisotropy, a field produced by a magnetization vector with non-zero divergence is not a Laplacian field; the latter is often not the most appropriate type of field. The outer layers **27** and **27'''** may, for present purposes, be doped with larger amounts of, say, gallium than the inner layers **27'** and **27''**, the larger amounts of gallium being effective to increase H in the layers **27** and **27'''** for a given applied field. An appropriate amount of dopant can be provided in each layer, using the teachings in the Anderson et al. article, to give the required profile of the bias field H.

The discussion with reference to FIGS. **5** through **11** relates to situations where the magnetic bias field H and the wave energy are generally *z*-directed, the angle ψ being typically less than 1° from the *z* direction. It can be seen from the mathematical expressions that similar results obtain when the external field is oriented near a direction $\pi/2$ radians from the *z*-directed field previously discussed. However, whereas an applied field of 2,000 gauss, typically will be required to provide a *z*-directed internal field H of about 300 gauss (for example, to convert a 1,000 Hz. electromagnetic signal to a spin wave), a 300 gauss external field directed in the plane of the material (in which ω_M is $\approx \pi \cdot 10^{10}$ radians/sec) will result in an internal field H of about 300 gauss. However, to shift the field from $+\psi$ to $-\psi$, for example, requires more power when the field generally is directed in the plane of the material than when the field is directed generally in the z direction. (It should be here noted that the crystals discussed herein may measure typically a few spin wave lengths in the z-direction but tens of wavelengths in cross dimensions.)

As previously mentioned, when wave energy within the magnetic material is at or near the value k_x (values of k within the range $n=\frac{1}{2}$ to $n=3$ are considered near k_x for present purposes), appreciable time delay can be obtained. In the absence of loss a theoretical delay time of the order of 2.5 microseconds in 10^{-3} cm. is possible

in YIG, thus rendering the present invention useful, also, in connection with thin film devices.

In the prior discussion it is shown that the group velocity of the propagating wave is quite sensitive to changes in the internal magnetic bias field H, which, in turn, is a function of the external field. It is possible, therefore, by noting changes in the group velocity, i.e., time delay, to relate such changes to the changes in the external field thereby to determine the magnitude of any changes in the external field. The circuitry disclosed in FIG. 7 can thus be used to provide a measure of the external field.

References to the wavenumber k in the present specification relates in all instances to the propagation constant of the spin wave, and the decay rate α relates only to the reactive or evanescent decay; it should be noted, however, that a propagating spin wave in a non-ideal material has a decay rate, and the evanescent wave has a wavenumber. As previously noted, there can exist certain spin waves (even in the lossless case) have both an $\bar{\alpha}$ and $\bar{k}$. The effect of loss on these waves is to modify the $\bar{\alpha}$ and $\bar{k}$ values so as to produce attenuation in the direction of energy propagation. Also, the term electromagnetic is, by necessity, used in more than one context herein; an attempt has been made, however, at all times to make clear in what way the term is used. In air the power transfer and energy form of the propagating wave are both electromagnetic, but within the magnetic material described the spin wave power transfer mechanism is exchange and electromagnetic.

In the material the small signal energy density in both the propagating spin wave and the evanescent wave contain the factors shown in the following mathematical analysis:

$$W = \tfrac{1}{2}\,\epsilon|\bar{e}|^2 \text{ (electric)} + \tfrac{1}{2}\,\mu_o\,|\bar{h}|^2 \text{ (magnetic)} + \tfrac{1}{2}\,\mu_o\,(H_z/M_z)\,|\bar{m}|^2 \text{ (Zeeman)} + \tfrac{1}{2}\,\mu_o\,\lambda\,(\delta\,\bar{m}/\delta x_j)\cdot(\delta\,\bar{m}/\delta x_j) \text{ (exchange)} + \tfrac{1}{2}\,\mu_o\,N_{ij}^{a}\,m_i\,m_j$$

(magnetic anisotropy)

(summation over a repeated subscript is implied), where the terms "electric," etc., in parentheses designate the type of energy represented by the terms immediately preceding the parenthetical term. The elements in the immediately preceding analysis represent the following: W is the small signal (s.s.) energy density (joules/m^3); $\bar{e}$ is the s.s. electric field (volts/m.); ϵ is the permittivity of the material, i.e., the permittivity in air ($\epsilon_o \cong 1/36\pi \cdot 10^{-9}$ farads/meter) times the dielectric constant; μ_o is the permeability of free space ($4\pi \cdot 10^{-7}$ henries per meter); h is the magnetic field (amperes/m); H_z is the internal d-c magnetic field (amperes/m); M_s is the saturation magnetization (amperes/m); $\bar{m}$ is the s.s. magnetization (amperes/m.); λ is the exchange constant (m^2); and $N_{ij}^{a} = N_{ij}^{a}$ are dimensionless constants which depend upon orientation of the crystal relative to the internal d-c field H, the term $N_{ij}^{a}\,m_i\,m_j$ upon expansion taking the form $N_{11}^{a}\,m_1^2 + 2N_{12}^{a}\,m_1\,m_2 + N_{22}^{a}\,m^2$, where: $m_1 = m_x$, $m_2 = m_y$ and $m_3 = m_z$.

Further, the s.s. power flux (watts/m^2) is represented by

$$(\bar{s})_i = (\bar{e} \times \bar{h})_i - \mu_o\,\pi\,(\delta\bar{m}/\delta x_i)\cdot(\delta\bar{m}/\delta t),$$

where: the s.s. power $(\bar{s})_i$ = the sum of the small signal power fluxes in the x, y and z planes.

The principles discussed herein may be used as a basis for constructing devices in which a magnetic material is placed to couple an input transmission line to a plurality of output transmission lines and to switch output power from one to the other of these outputs as in a strip line or the like, or to provide a microwave computer function such as binary switching.

The discussion to follow is concerned primarily with the concept of doping the YIG crystal to provide material parameters or characteristics which, in combination with the external magnetic bias field $\bar{H}$, provide an internal bias field H profile of a predetermined shape or contour. Thus, the magnetic field profiles shown in FIGS. 2B, 2C and 2D in said U.S. Pat. No. 3,530,302 in the rod 1 of FIG. 6A thereof can be provided. It will be appreciated, also, that other profiles can be furnished as needed, e.g., a magnon tunnel transducer particularly useful at frequencies above S-band (3,000 MH_3) and into X-band and higher. Such transducers have graded values of saturation magnetization $4\pi M_s$, as discussed previously herein and as now discussed in connection with the layers **27**, **27'**, **27''**, **27'''** in FIG. **11**. For example, the layers **27** and **27''** can each be the order of 50–100 microns thick and in a uniform z-directed external field $\bar{H}$ applied to a device having graded susceptibility could provide a gradient in the saturation magnetization of say 50,000 oe/cm. The saturation magnetization $4\pi M_s$ at the input end **28** of the device **40'''** could be ~ 1,750 oersteds and the saturation magnetization $4\pi M_s$ at the right side of the layer **27** could be ~ 1,250 oersteds, for example. The layer **27'''** on the other hand, could have a saturation magnetization $4\pi M_s$ of ~ 1,750 oersteds at the end **29** and ~ 1,250 oersteds at the inside and thereof, and the layers **27'** and **27''** can have uniform saturation magnetization $4\pi M_s$ ~ 1,250 throughout. The conversion from photon-to-magnon-to-phonon would occur in the layer **27** and reconversion in the layer **27'''** of such device. The layers **27** and **27'''** in the device **40'''** can be epitaxially grown on the respective ends of a single bulk crystal in the manner hereinafter discussed. Input and output could be effected by the fine-wire coupling shown in said U.S. Pat. No. 3,530,302 or by the arrangement shown in FIG. 7 hereof. The layer **27** serves to transduce input photons to magnons which rapidly tunnel into the epitaxial layer **27** to a region at which tunneling yields to propagation, after which conversion to phonons occurs. The time required for tunneling and conversion is inversely proportional to the magnitude of the gradient of the effective field within the layer **27**, which in this instance, is about equal to the magnitude of the gradient of the saturation magnetization $4\pi M_s$. At the layer **27'''** the reverse occurs. A discussion of the methods of doping to provide changes in susceptibility is found previously herein and in the following two paragraphs. It should be hereinnoted, however, that the crystals upon which work has been done to date are $3Y_2O_3 \cdot (5-X)\,Fe_2O_3 \cdot XGa_2O_3$ where $0<X<1$ (representing pure YIG and Ga YIG, respectively) and the following saturation magnetization $4\pi M_s$ values obtain:

X = 0.2 $4\pi M_s \cong$ 1430 oersteds
X = 0.6 $4\pi M_s \cong$ 890 oersteds
X = 1.0 $4\pi M_s \cong$ 350 oersteds;

and that the magnetizing field $\bar{H}$ used is the order of 500 to 2,000 gauss.

A number of methods may be employed to grow graded-parameter crystals for the above purposes; two such methods are described in this and the following paragraph and they relate respectively to thin films and bulk crystals. The method described in the instant paragraph is that of chemical vapor deposition for preparation of thin films. Single crystal YIG is deposited according to a chemical reaction occurring at the vapor-crystal interface in which gaseous yttrium and iron halides react with water vapor and/or oxygen to produce $Y_3Fe_5O_{12}$. The metal-halide vapors needed for these reactions are produced in a furnace by passing a halide (e.g. chlorine) gas over hot metal powder of iron and yttrium in the first zone of a furnace, deposition upon a substrate occurring at a second zone in the furnace. The furnace is controlled to provide typically a temperature ~ 1,150°C in the halide generation zone and 1,100° to 1,400°C in the chemical vapor deposition zone. A pressure of 2 to 10 Torr was used in actual apparatus; a gas flow of 150 cc/minutes; and the run times were 30 to 120 minutes. Gallium to give the graded parameter crystals can be added as gallium halide gas in the chemical vapor deposition zone.

Bulk crystals have been grown by the top-seeded method to lengths of 2 centimeters and up to 4 centimeters in diameter in a non-stoichiometric melt using $BaO—B_2O_3$ as the solvent. Melts containing from 18 to 26 weight percent YIG give crystalization of the garnet phase in a temperature range between 1,000°C and 1,250°C. Gallium can be introduced into the melt during the growth process, but other means for introducing the gallium may be used. Thus, for example, a YIG crystal grown to size without doping and polished can be dipped at each end, into a solution of Ga-YIG at a temperature of 1,100°C for 15 minutes, and the gallium in the solution will chemically replace some of the iron in the YIG at the ends to give a spatially non-uniform thin film at each of the two ends. (See two journal articles by R.C. Linares entitled "Substitution of Aluminum and Gallium in Single-Crystal Yttrium Iron Garnets," Journal of American Ceramic Society, pp. 68–78, Vol. 48, No. 2, February, 1965, and "Growth of Single-Crystal Garnets by a Modified Pulling Technique," pp. 433–4, Journal of Applied Physics, Vol. 35, No. 2, February, 1964). The graded film, thereby formed, provides the quantum mechanical tunneling properties of a single-crystal film which can act to transduce the photon input energy by converting that input to the magnon and phonon forms before mentioned. The graded film, which can typically be ~50–100 microns thick is made up of a series of such contiguous layers (by repetitive dipping into Ga-YIG solutions having different ratios of Ga and Fe) one or more microns thick which vary from layer to layer to give, essentially, a continuous change in magnetization from one end to the other. The graded film can be the layers **27** and **27'''** in FIG. **11**. Similar effects can be provided by appropriate masking of the crystal to produce the various configuration shown in FIGS. **9** and **10**. It will be appreciated that the layers **27** and **27'''** and the layers in several of the other figures can be grown by the chemical deposition method previously discussed. It will be further appreciated that the internal magnetic bias field H, which is a function of $\bar{H}$ plus the material parameters, can be electronically tuned by effecting changes in $\bar{H}$.

The term "susceptibility" as used herein is an extension of the Polder magnetic susceptibility tensor generalized to include spatial, as well as temporal, dispersion in its components. This tensor includes the effects of coupling among spin waves, elastic waves and the electromagnetic fields. A system comprising electromagnetic power, spin wave power, and elastic wave power can be viewed as an equivalent electromagnetic system provided the concept of the Polder magnetic susceptibility tensor is extended to include spatial as well as temporal dispersion in its components. This dispersion accounts for the coupling among spin waves, elastic waves and electromagnetic waves.

Further modifications of the invention herein disclosed will occur to persons skilled in the art and all such modifications are deemed to be within the spirit and scope of the invention as defined in the appended claims.

What is claimed is:

1. An article for processing electromagnetic wave energy, that comprises, a magnetic material adapted to receive the electromagnetic energy, the material being one that will support propagating spin wave energy, the material being one in which the electromagnetic wave energy can be converted to propagating spin wave energy and in which the direction of the group velocity of the propagating spin wave can be varied by varying at least one of the magnitude and direction of a magnetic bias field within the material, the material being further adapted to receive an applied magnetic field which in combination with the magnetic characteristics of the material provides the internal magnetic bias field needed to effect spatial conversion from electromagnetic power to propagating spin waves, the spin waves being carried in the electromagnetic channel, the quantum mechanical exchange channel or a combination thereof, the material being doped to provide a predetermined grading of said magnetic characteristics thereby to provide a predetermined profile of internal magnetic bias field, said material comprising a plurality of adjacently disposed layers each presenting different material parameters to the energy, said conversion being effected by passing the wave successively from one to the other of the layers, thereby to subject the electromagnetic wave to a plurality of successive discontinuities at the interfaces of the said layers to provide the abrupt spatial conversion.

2. An article for processing electromagnetic wave energy, that comprises, a magnetic material adapted to receive the electromagnetic energy, the material being one that will support propagating spin wave energy, the material being one in which the electromagnetic wave energy can be converted to propagating spin wave energy and in which the direction of the group velocity of the propagating spin wave can be varied by varying at least one of the magnitude and direction of a magnetic bias field within the material, the material being further adapted to receive an applied magnetic field which in combination with the magnetic characteristics of the material provides the internal magnetic bias field needed to effect spatial conversion from electromagnetic power to propagating spin waves, the spin waves being carried in the electromagnetic channel, the quantum mechanical exchange channel or a combination thereof, the material being doped to provide a prede-

termined grading of said magnetic characteristics thereby to provide a predetermined profile of internal magnetic bias field, said magnetic material comprising a plurality of regions, the material parameters varying from region to region.

3. An article as claimed in claim 2 and in which the regions are a plurality of layers adjacently disposed along the path of travel of the spin wave power, said conversion being effected by passing the wave energy successively from one to the other of the layers thereby to subject the wave energy to a plurality of successive discontinuities at the interfaces of said layers to provide abrupt spatial conversion.

4. An article as claimed in claim 2 and in which regions are transversely disposed within the material, the material being adapted to receive an applied magnetic field, the effect of which in combination with the material parameters being to provide a plurality of different-valued environmental parameters to the wave energy from region to region.

5. An article for processing electromagnetic wave energy, that comprises, a magnetic material adapted to receive the electromagnetic energy, the material being one that will support propagating spin wave energy, the material being one in which the electromagnetic wave energy can be converted to propagating spin wave energy and in which the direction of the group velocity of the propagating spin wave can be varied by varying at least one of the magnitude and direction of a magnetic bias field within the material, the material being further adapted to receive an applied magnetic field which in combination with the magnetic characteristics of the material provides the internal magnetic bias field needed to effect spatial conversion from electromagnetic power to propagating spin waves, the spin waves being carried in the electromagnetic channel, the quantum mechanical exchange channel or a combination thereof, the material being doped to provide a predetermined grading of said magnetic characteristics thereby to provide a predetermined profile of internal magnetic bias field, said material being a thin film comprising a plurality of adjacent layers disposed along the path of travel of the propagating wave energy within the material, the magnetic characteristics of the material differing from layer to layer thereby to provide said abrupt discontinuity as a series of smaller discontinuities.

6. An article for processing electromagnetic wave energy, that comprises, a magnetic material adapted to receive the electromagnetic wave energy, the material being one that will support propagating spin wave energy and propagating elastic wave energy, the material being one in which the electromagnetic wave energy can be converted to propagating spin wave energy and elastic wave energy, the material being further adapted to receive an applied magnetic field which in combination with the magnetic characteristics of the material provides the internal magnetic bias field needed to effect spatial conversion from electromagnetic power to propagating spin waves and elastic waves, the material being treated to provide a predetermined grading of said magnetic characteristics, said material being rod-like in form and the regions at the end faces thereof being doped to form a graded thin film ~50 to 100 microns thick at each end face.

7. An article as claimed in claim 6 in which the crystal is YIG and in which the saturation magnetization $4\pi M_s$ of the film varies from 1,430 oersteds to 350 oersteds.

8. An article for processing electromagnetic wave energy, that comprises, a magnetic material adapted to receive the electromagnetic wave energy, the material being one that will support propagating spin wave energy and propagating elastic wave energy, the material being one in which the electromagnetic wave energy can be converted to propagating spin wave energy and elastic wave energy; the material being further adapted to receive an applied magnetic field which in combination with the magnetic characteristics of the material provides the internal magnetic bias field needed to effect spatial conversion from electromagnetic power to propagating spin waves and elastic waves, the material being treated to provide a predetermined grading of said magnetic characteristics, said material having two end faces separated by an interior portion, said end faces containing a thin film of non-uniform material parameters to give graded values of material saturation $4\pi M_s$ at said end faces, the graded values of the thin film acting with said applied magnetic filed to provide the desired contour of the internal magnetic bias field.

9. An article as claimed in claim 8 in which said material is a crystal which contains at said end faces controlled gradients of the concentration of impurities, thereby to control the frequency and/or wavelength dependent susceptibility within the crystal at the region of said end faces and within said thin film.

10. An article as claimed in claim 9 in which the thin film at each of the end faces is on the order of ~50 to 100 microns thick.

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