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ELECTROMAGNETIC WAVE GENERATION UTILIZING ELECTRON SPINS IN MAGNETIC MATERIALS

Filed Nov. 10, 1960 2 Sheets-Sheet 1

FIG. 1A

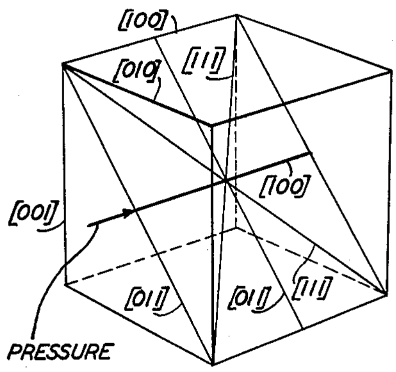

FIG. 1

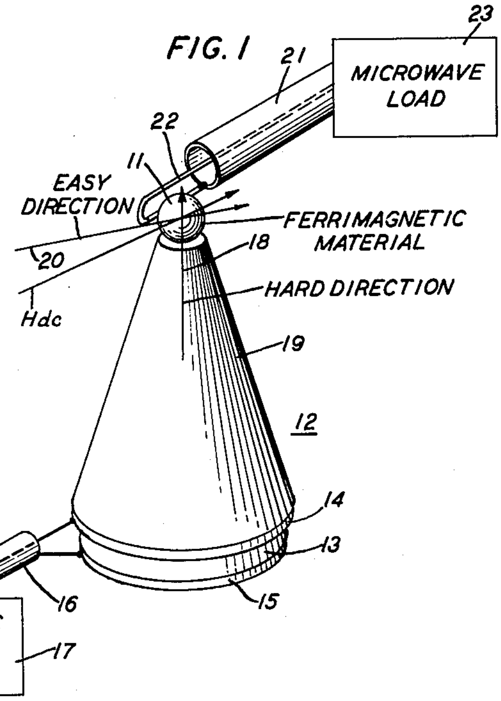

FIG. 2

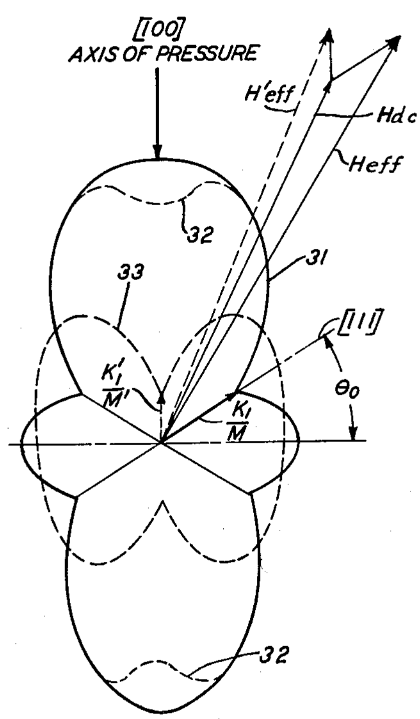

FIG. 3

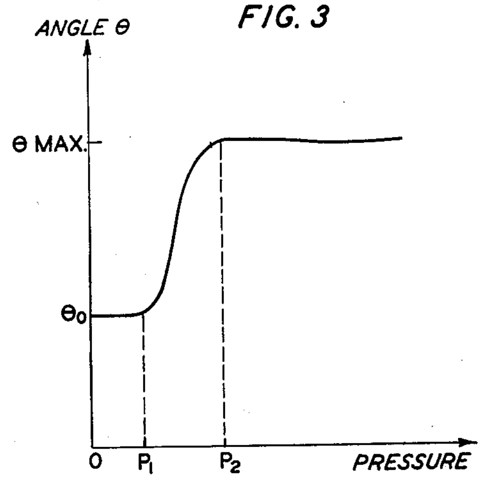

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FIG. 4

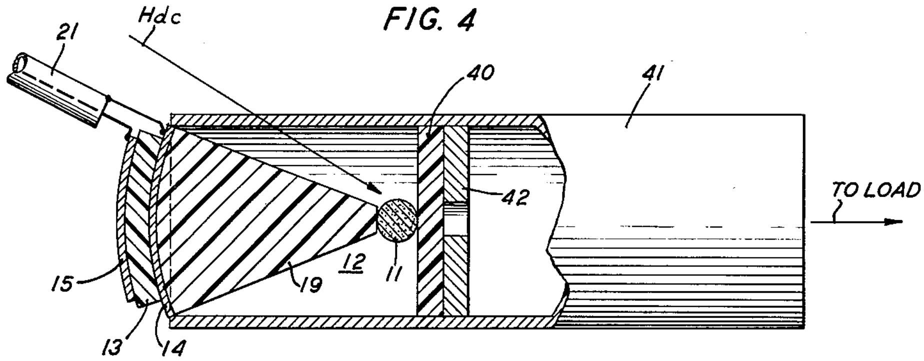


FIG. 5A

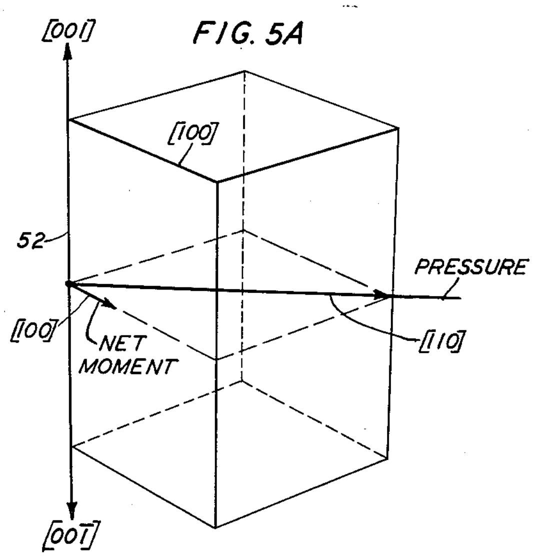
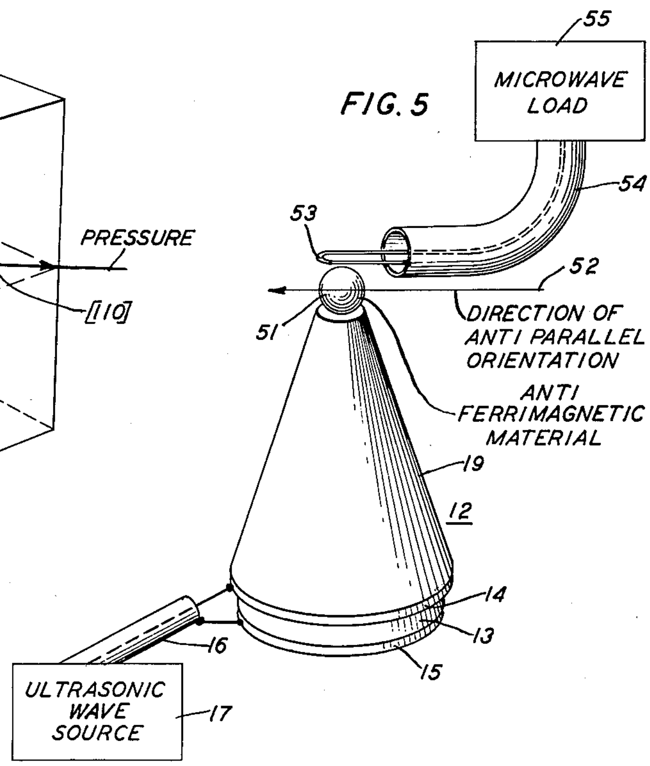


FIG. 5



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ELECTROMAGNETIC WAVE GENERATION UTILIZING ELECTRON SPINS IN MAGNETIC MATERIALS

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11 Claims. (Cl. 331—94)

This invention relates to methods and means for electromagnetic wave generation, and more particularly, to the production of either pulses or continuous radiation of high frequency wave energy in the microwave and millimeter wave range by direct conversion of low frequency, ultrasonic acoustical energy into high frequency radio energy.

It is an object of the present invention to generate microwave and millimeter wave energy through stimulation of the electron spins in magnetic materials.

In United States Patent 2,873,370, Robert V. Pound has disclosed how high frequency pulses may be developed by utilizing the gyromagnetic effects which are observed in materials which are paramagnetic, ferromagnetic or ferrimagnetic. With the application of a direct current magnetic field, referred to hereinafter as the biasing field, the axes of the electron spins within these materials are aligned with the field. If the spin axis is momentarily deflected from this relationship with the biasing field, it will not return to its original position immediately but will precess about the biasing field at a frequency proportional to the magnitude of the biasing field. This frequency is called the gyromagnetic resonance frequency. The equilibrium condition will eventually be re-established by various damping factors in a period designated as the relaxation time of the spin system.

Pound has pointed out that if the direction of the biasing field can be changed by a substantial amount in a time short compared with the relaxation time, the resulting precessional motion will generate its own electromagnetic fields. If this body is magnetically coupled to a resonant circuit which in turn is coupled to a load, energy from this generated field may be delivered to the load. Further details and analysis may be found in the above-identified patent.

In practice, however, it is obviously very difficult to produce a sufficient change in the large biasing fields required and to produce this change in a short enough time with external coils or similar field producing means. Even under the most favorable conditions the limitations on the magnitude and the time of change in the biasing field severely limit the frequency, power and duration of the generated pulses of microwave energy. It would be necessary to produce changes in fields of several 100 oersteds in a time in the order of 10^{-8} seconds, for example, a requirement impossible to meet without extremely bulky equipment.

However, it has been discovered in accordance with the principles of the present invention that a physical or mechanical distorting pressure applied to an anisotropic material will alter the magnetocrystalline anisotropy energy of the material. Since the crystalline energy implies an equivalent magnetic field equal to the second derivative of the energy with respect to orientation, the effect on the magnetic spins is substantially identical to the effect of altering the external magnetic field. Particularly, a distorting pressure will alter either the direction or magnitude or both of the effective internal magnetic field of the material determined by the magnetocrystalline energy, even though the external field remains unchanged. It will be recalled that an anisotropic material is one having magnetic properties that are different in different directions so that the magnetization tends to be directed along certain definite crystallographic axes.

The principles of the invention may be practiced with any material that shows strong magnetostrictive effects, that is, a change in the magnetocrystalline structure of the materials and its internal magnetic energy with deformation even though the material is not ordinarily considered as gyromagnetic.

This will be understood when it is recalled that the total magnetocrystalline energy of the spin system of all crystalline solids containing atoms having uncompensated spins is made up of the sum of three components: the energy due to spin-orbit interaction, the energy due to dipole-dipole interaction, and the energy of exchange interaction between neighboring spins.

In paramagnetic materials the exchange energy is small while the dipole-dipole energy and/or the spin-orbit energy are significant in causing so-called zero-field-splitting or magnetic anisotropy. In ferromagnetic, ferrimagnetic and antiferromagnetic materials the exchange energy is also large, and its effect is to produce either parallel or antiparallel alignment of the spins of neighboring atoms. In the case of ferromagnetic and ferrimagnetic materials this gives rise to a large magnetic moment due to the spins of many atoms acting in concert while in antiferromagnetic materials the spins are divided into two equal antiparallel sublattices whose magnetic moments just neutralize each other so that the material has no appreciable external magnetic moment. Even in materials having a large exchange energy, the dipole-dipole energy and/or the spin-orbit energy determine the anisotropy energy and the specific crystallographic directions along which the spins of one or more sublattices prefer to lie. On the other hand, the exchange energy determines the extent to which the spins of neighboring atoms tend to remain aligned (parallel or antiparallel) with each other.

These characteristics effect the resonance frequency of the material in the following way. In ferromagnetic and ferrimagnetic resonance, all spins act in concert at a resonance frequency proportional to a magnetic field function, designated the internal effective field H_{eff}, which essentially comprises the vector sum of the external biasing field and the anisotropy field. In antiferromagnetic resonance the mode of resonance is characterized by one of the sublattices moving with respect to other, and so the effective field H_{eff} is expressed by a function to be set out hereinafter which includes a term representing also the exchange energy field. This exchange field is so large that the contribution of the externally applied field to the resonance frequency is small and, therefore, the external field is not essential to produce resonance at high microwave frequencies in anti-ferromagnetic materials.

It is, therefore, a more specific object of the invention to mechanically strain or distort the crystalline structure of an element of ferromagnetic, ferrimagnetic, paramagnetic or antiferromagnetic material, thereby varying the anisotropy component of the magnetocrystalline field within the material and to utilize the resulting electron precession to generate electromagnetic wave energy.

The last mentioned object of the invention is accomplished in accordance with embodiments to be described hereinafter by employing an ultrasonic transducer to continuously exert periodic acoustic pressures upon such a sample to produce a wave train of microwave radio pulses. In particular, in the ferromagnetic and ferrimagnetic embodiments to be described, the pressure is applied along the hard axis of magnetization of a sample that is biased by a static magnetic field at an acute angle to the easy axis. The pressure produces a shift in the position of the anisotropy field and, therefore, a shift in the position of the total magnetic moment of the material. Electron precession from the original position to the new position of the moment will produce radiation at the ferromagnetic resonance frequency of the material.

In the antiferromagnetic embodiment, the pressure is applied along an axis at an angle to the antiparallel direction, that is, the direction along which the individual sublattices are originally directed. This causes one or more of the sublattices to move out of antiparallelism and to produce a net moment in the plane normal to the antiparallel axis. The electrons will precess back into alignment during the transit period following the deformation as the sublattices return to equilibrium with their surroundings and will radiate electromagnetic wave energy at the antiferromagnetic resonance frequency during this period. This radiation takes place whether or not the material is biased by an external field.

The resulting microwave energy from either embodiment constitutes a primary source of energy useful for pumping masers and parametric amplifiers, for use in high resolution radar systems, or for any other application requiring simply generated high frequency energy.

Despite the fact that magnetostriction and related effects are associated with materials used to practice the invention, the principles of the invention must not be confused with piezomagnetic, piezoelectric, magnetostrictive and other similar devices that ordinarily make use of the properties of these materials in the prior art. These devices are similar in that a periodic mechanical pressure is used to produce periodic electrical energy. However, it is important to recall that the frequency of the electrical energy so produced is the same as the frequency of the mechanical variation. By contrast, a relatively low frequency mechanical variation in accordance with the present invention will produce electromagnetic wave energy of frequency many times greater.

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

In the drawings:

FIG. 1 is a schematic showing of an illustrative embodiment of the invention utilizing the properties of ferromagnetic, ferrimagnetic or paramagnetic materials;

FIG. 1A is a representation of the crystal structure of a preferred cubic material for use in the embodiment of FIG. 1;

FIG. 2 is a polar plot of a typical anisotropy energy surface given for the purpose of explanation;

FIG. 3 is an illustrative plot of the shift in magnetization with respect to pressure;

FIG. 4 illustrates how the principles of the invention may be applied to a conductively bounded waveguide embodiment;

FIG. 5 is a schematic showing of an illustrative embodiment of the invention utilizing the properties of antiferromagnetic materials; and

FIG. 5A is a representation of a crystal of a preferred material having a tetragonal structure for use in the embodiment of FIG. 5.

Referring more particularly to FIG. 1, the basic components of an illustrative embodiment of a ferromagnetic, ferrimagnetic or paramagnetic wave generator in accordance with the invention are shown schematically. Sphere **11** represents the active element of material which is mechanically connected to an ultrasonic transducer **12**. In this emodiment sphere **11** may be made of any of the several non-conductive, high anisotropy magnetic materials exhibiting pronounced piezomagnetic effects and also gyromagnetic effects at microwave frequencies and above. For example, it may be one of the cubic ferrimagnetic spinels such as single crystal ferrite, a ferrimagnetic hexagonal crystal such as ferroxdure, one of the ferrimagnetic materials such as yttrium iron garnet or one of many ferromagnetic or paramagnetic materials. In the specific embodiment which is here described, it will be assumed that sphere **11** in one of its preferred forms is made of a single crystal of yttrium iron garnet.

The shape of element **11** has been indicated as spheroidal which presently appears to be the preferred form, but it should be noted that the exact shape depends upon a complicated relationship between the demagnetizing effects in the element and the physical response of the element to pressure waves. Therefore, the exact shape must be determined in a particular case by empirical methods and may be lenticular, ovoid, square, or rectangular in shape. The size of sphere **11** is such that it is mechanically resonant to the ultrasonic pressure waves and so depends upon the frequency of the pressure waves and their wave length within the particular material. In particular, it has been found that an yttrium iron garnet sphere of approximately fifteen mils in diameter is resonant at approximately ten megacycles. Such a resonance intensifies the pressure variations upon the crystal lattice of the material.

Sphere **11** is acoustically excited by any suitable means for generating a vibration of ultrasonic frequency, for example, in the order of 10^7 cycles per second. A preferred method is to employ a transducer **12** of which many types are known to the art using suitable materials having strong piezoelectric effects such as quartz or barium titanate. For example, a number of such transducers and their methods of operation are described in the textbook "Piezoelectric Crystals and Their Application to Ultrasonics," by W. P. Mason. In the embodiment illustrated, transducer **12** comprises a segment **13** of barium titanate shaped as a circular segment of a spherical shell. The ultransonic frequency generated by transducer **12** is determined by the resonant thickness of segment **13**. For resonance of ten megacycles it has been found that the thickness of barium titanate should be in the order of ten mils. Similarly shaped electrodes **14** and **15** of thin conductive material are bonded to the inner and outer surfaces of segment **13**, respectively. Electrodes **14** and **15** are connected to the conductors of the coaxial line **16** which, in turn, is connected to an electrical source **17** of wave energy of ultrasonic frequency.

In order to concentrate the energy upon sphere **11** transducer **12** further includes a focusing member **19** which makes the mechanical connection between segment **13** and sphere **11**. In the embodiment illustrated, member **19** takes the form of a cone of dense dielectric material, such as fused silica or quartz, having a spherical base surface that mates with and is suitably bonded to electrode **14**. The opposite end is slightly truncated to mate with sphere **11**. It is of particular importance that sphere **11** be oriented with its axis of hard magnetization aligned with the direction of pressure for the reasons to be developed in greater detail hereinafter. In FIG. 1, the hard axis of sample **11** is designated by vector **18** which is oriented to be coincident with the conical axis of member **19**. It has been found that an epoxy resin or a rubber cement is suitable for bonding sample **11** to the truncated end of member **19** with this orientation. Suitable support means, not illustrated, may be provided in accordance with usual practice near the conical base of member **19**.

It is not within the scope of this disclosure to develop the crystallography of the many materials that may be used to practice the invention. However, it is necessary to understand that the anisotropy energy of a ferromagnetic crystal acts in such a way that the magnetization tends to be directed along certain definite crystallographic axes which are called directions of easy magnetization; the directions along which it is most difficult to magnetize the crystals are called hard directions. Historically, these directions have been determined empirically. However, the location of each of these directions with respect to the crystal structure is now well known for each particular crystal and may be found in any standard text. For example, the easy direction of a hexagonal crystal is generally along the hexagonal axis and the hard direction at right angles to this axis. This may change, however, in the presence of certain additives. FIG. 1A illustrates the crystal structure and the conventionally designated axes for the particular case of cubic yttrium iron garnet. Thus, the cube edges are designated the [100], [010] and [001] axes and are the directions of hard magnetization. The body diagonals are designated [111] and equivalent axes and are the easy directions.

Having thus taken into account the particular hard and easy directions of magnetization of the material of sphere **11**, and having aligned the hard direction [100] thereof with the pressure from member **19**, means are provided for applying a steady, unidirectional biasing field to element **11** at an angle between the hard and easy directions. In FIG. 1 the easy direction is represented by the vector **20** and the direction of the biasing field by the vector H_{dc}. The precise means for producing this field is not illustrated since it may be produced by placing element **11** between the pole pieces of any suitable solenoid or permanent magnet structure as is now conventional in the gyromagnetic art. The strength of the biasing field is such as to at least saturate element **11** and of such a strength above saturation to produce gyromagnetic resonance within element **11** at the frequency of the desired output microwave energy.

Means are provided for coupling with the magnetic flux generated by the resulting electron spin precession within element **11** and for delivering the energy thus generated to a useful load. Thus, the coupling may comprise a coaxial conductor **21** which terminates in a small loop **22** in close proximity to element **11**. Since the time varying component of the flux exists substantially normal to the biasing field, the plane of loop **22** is substantially parallel to the biasing field H_{dc}. The size of loop **22** and its spacing from element **11** are such as to produce a condition of tight coupling. For this condition the radiation damping is approximately equal to the spin-lattice damping and corresponds to a perfect match between the electromagnetic structure and the spherical sample at ferromagnetic resonance. This affords the maximum transfer of energy to the useful load represented by **23** which is connected to the other end of coax **21**.

In practice, sphere **11**, loop **22** and all or part of transducer **12** may be included in a conductive shield which may or may not play a part in the coupling between loop **22** and sphere **11**. In certain embodiments, to be described hereinafter, this shield takes the form of a resonant cavity, which itself provides the coupling means to receive the generated energy.

Having thus described the components and their combination in accordance with the invention, some attention will now be given to the preferred mode of operation and to the theory underlying this operation. Referring, therefore, to FIG. 2, the solid curve **31** represents a polar plot of the anisotropy energy surface of a cubic crystal in its unstressed condition. The hard axis of magnetization represented by [100] has the largest anisotropy energy. The easy axis represented by [111] has the smallest anisotropy energy. The anisotropy energy along the axis [111] can be represented approximately by a magnetic field of magnitude K_1/M where a K_1 is the first term of the anisotropy constant and M is the magnetization. Thus, when the biasing field H_{dc} is applied at some angle to the easy axis [111], the total effective field H_{eff} within the material is the vector sum of H_{dc} and K_1/M and may be represented on FIG. 2 by the vector H_{eff} between H_{dc} and K_1/M. When the biasing field is applied, the electron spins precess about H_{eff} during the effective spin relaxation time at a frequency $\omega=\gamma H_{eff}$ where γ is the gyromagnetic ratio. After the relaxation time, H_{eff} represents the equilibrium position of the spins.

Now when pressure is applied along the hard axis of the material, the anisotropy energy surface will be altered. With the application of small pressure, a dent, such as **32** on FIG. 2, in the anisotropy energy curve appears along the axis of pressure. This small pressure does not change the direction of the magnetization of the material. As pressure is increased, however, the dent **32** becomes deeper and eventually the pressure induced minimum becomes the lowest energy position. This condition is represented by the dotted curve **33** showing the new anisotropy energy system under stress. Then, rather abruptly, the magnetization of the sample is drawn toward a new position with the axis of easy magnetization now aligned with the axis of pressure. The total effective field is now the vector sum of H_{dc} and the new anisotropy field K_1'/M as shown on FIG. 2 by H_{eff}' which represents a new equilibrium position.

The way this shift in the easy direction of magnetization takes place is shown in FIG. 3 by the plot of the angle of the easy direction from an arbitrary reference versus the pressure applied. The curve indicates that for pressures below the pressure designated P_1, the direction of the easy magnetization is not changed. At the pressure P_1 the angle begins to increase rapidly to reach its maximum at P_2 for which the easy axis is now substantially aligned with the direction of pressure.

If the pressure makes the excursion described above from zero to a value exceeding P_2 in a time t, the sudden angular change of H_{eff} from the positions represented by θ_0 to θ_{max} will take place in a time in the order of $t/10$ or less. If $t/10$ is short compared with the relaxtion time of the spin system, the spins precess from the original position of H_{eff} to the new position H_{eff}' and will excite radiation at the frequency $\omega=\gamma H_{eff}'$. Note that in absolute amplitude H_{eff}' will not be substantially different from H_{eff}.

Now when a sinusoidal pressure wave from transducer **12** is applied to sphere **11**, an almost discontinuous change in the orientation of H_{eff} wil be achieved. In accordance with the invention it is contemplated that the frequency of this pressure wave will be in the ultrasonic range and of the order of ten megacycles. The change in orientation of the easy axis will take place at approximately 10^{-8} seconds. Since materials such as single crystals of yttrium iron garnet have relaxation times as long as 10^{-6} seconds, the precessional motion produced during each interval of rapidly changing internal field will persist substantially undiminished until the next cycle of the ultrasonic wave reinforces the precession. Thus, a continuous radiation of microwave energy is produced. The precessional motion has a selectable frequency within a broad range in the microwave and millimeter wave bands, that is, a frequency of several thousand megacycles and higher.

FIG. 4 illustrates one of the many possible ways in which the principles of the invention may be applied to a physical waveguide embodiment and also illustrates the important principle of static pressure biasing. Reference to FIG. 3 above will indicate that valuable time and exciting energy is expended in the embodiment of FIG. 1 in varying the pressure through the region from zero to the pressure P_1. It is thus proposed to pressure bias the sample with a static pressure just below the pressure P_1. Thus, the required excursion of variable pressure is substantially reduced.

In FIG. 4 static pressure is applied by backing sphere **11** with a plate **40** of dielectric material. A section **41** of conductively bounded waveguide of circular cross-section is employed. The right end of guide **41** is connected to the utilizing load and the left end thereof contains the ultrasonic transducer **12**. Since transducer **12** may be identical to the one described with reference to FIG. 1, corresponding reference numerals have been employed. The spherical shape of electrode **14** makes it possible to connect it electrically and mechanically to the end of guide **41** and, thus, to serve as the conductive end plate of guide **41**. Plate **40** is in the form of a disc and presses sphere **11** with the desired biasing pressure against the end of pressure focusing member **19**. Adjacent to plate **40** is an iris **42** of conductive material which forms a resonant cavity with **14** in guide **41**. Sphere **11** is magnetically biased by the field H_{dc} suitably applied at an angle as described above. Thus, the cavity is excited by sphere **11** in a more or less circularly polarized mode.

While the foregoing analysis has been made in terms that are usually applied to ferromagnetic or ferrimagnetic materials, it should be noted that the principles of the invention apply also to materials that are paramagnetic, even though the explanation of effects in paramagnetic materials is conventionally described in quantum mechanical terms. Thus, the application of pressure would be described in terms of "zero-field-splitting" as producing an interchange in the population between a set of energy levels. It is not within the scope of this disclosure to resolve the differences in terminology used by the art and it should be sufficient to state that paramagnetic materials have known gyromagnetic ratios and known relaxation times with respect to which the preceding analysis can be applied. While they are not usually thought of as having "hard and easy directions of magnetization" they do have known directions along which the application of pressure will alter the energy level distribution which, for the purposes of the present invention, is equivalent to altering the direction of easy magnetization. A particular example of a suitable paramagnetic material is cerium ethyl sulfate, known to have a large zero-field-splitting for small distortions.

The case of antiferromagnetic materials is slightly different and the modifications necessary to employ this material are illustrated in FIG. 5. Since the details of the ultrasonic transducer **12** are identical to those employed in FIG. 1, corresponding reference numerals have been used to identify corresponding components. Referring to FIG. 5, modification will be seen to reside in the orientation of sample **51** of antiferromagnetic material, the absence of a biasing magnetic field, and the orientation of the pick-up loop **53**. Specifically, sample **51** is orientated so that the known antiparallel direction of the particular material is at some angle to the direction of pressure from transducer **12**. The antiparallel direction is that defined above as the direction along which the individual sublattices of the particular material prefer to be aligned in the orientation typical of antiferromagnetic materials. The optimum angle between the axis of pressure and the antiparallel direction cannot be generalized for all materials since it depends upon the crystal symmetry of the particular material employed. However, it is specifically known from piezomagnetization experiments that distortion along a given axis will produce a net magnetic moment along another given axis and these axes are those contemplated by the invention. A preferred example of antiferromagnetic material is cobalt fluoride and the tetragonal crystal structure of this material as shown in FIG. 5A with conventional coordinates designating the various crystal axes. The antiparallel axis **52** is the [001] and [001] axes with the oppositely directed vectors designating the antiparallel alignment of the two sublattices. For this particular material (and others of similar crystal symmetry) pressure applied along the [110] axis causes the individual sublattices to move out of antiparallelism and to produce a net moment along the [100] axis. Therefore, in FIG. 5 the axis **52**, representing the antiparallel direction, [001] and [00$\bar{1}$] is oriented to be normal to the axis of pressure.

In the ferromagnetic embodiment of FIG. 1, the pressure produced a change in the direction of the magnetocrystalline anisotropy field and the moment associated

with it. The electrons were required, therefore, to precess from one position to another. In the present antiferromagnetic embodiment, however, no net moment exists in the absence of pressure. With the appearance of the pressure generated moment along the axis [100], the electrons will precess back into alignment about the [001] direction during the period following the deformation at the antiferromagnetic resonance frequency provided that the period of the deformation is short compared with the relaxation time. As in the case of ferromagnetic resonance, the antiferromagnetic resonance frequency is $\omega=\gamma H_{eff}$ where γ is the gyromagnetic ratio for the antiferromagnetic material and H_{eff} is the total effective magnetic field within the material. In this embodiment H_{eff} includes the exchange interaction component H_E of the magnetocrystalline energy of the antiferromagnetic material as well as the anisotropy field H_A, and no external field is contemplated. However, the resonance frequency may be modified by the presence of an external biasing field H_{dc} directed along the antiparallel [001] axis in which case it adds or subtracts from the crystalline field as shown in the equation

$$H_{eff}=H_{dc}\pm[H_A(2H_E+H_A)]^{1/2}=\omega/\gamma$$

Thus, it is seen that two resonant frequencies are obtained separated by an amount $2\gamma H_{dc}$ both being vector sums of the exchange force component of the magnetocrystalline field within the material and the external biasing field if such a field is applied.

As in the previous embodiment the precessing electrons generate electromagnetic radiation which is picked up by loop **53** oriented with its plane normal to the [100] axis or vector **52** of FIG. 5. This energy is delivered by conductor **54** to load **55**. It should be understood, of course, that the principles of static pressure biasing and waveguide coupling as illustrated in FIG. 4 may be applied either separately or together to an embodiment of the invention employing antiferromagnetic resonance materials.

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

What is claimed is:

1. A generator of high frequency wave energy comprising
   - a body of material having a known gyromagnetic ratio, a relaxation time, an anisotropy crystalline field that varies with deformation of the material, and an internal effective magnetic field that includes said anisotropy field and the component of any external magnetic field applied to said body,
   - means for applying physical pressure to said body that varies in a period short compared to said relaxation time,
   - and means for coupling electromagnetic wave energy from said body at a frequency that is substantially equal to said gyromagnetic ratio multiplied by said internal effective magnetic field.

2. The wave generator according to claim 1 including means for applying a steady external magnetic field to said body,
   - said body being of ferromagnetic material for which said internal effective field comprises substantially the vector sum of said anisotropy field of said material and said external field.

3. The wave generator according to claim 1 wherein said body is of antiferromagnetic material for which said internal effective field includes a function of the exchange force field of said material.

4. A generator of high frequency wave energy comprising
  a body of material having an anisotropy crystalline field that varies with deformation of the material and an electron system that will precess in response to changes in said field,
  means including an ultrasonic transducer for applying a deforming physical pressure to said body that varies at an ultrasonic rate,
  and means for coupling from said body electromagnetic wave energy of at least microwave frequency generated by said electron precession.

5. A source of high frequency wave energy comprising
  an element of material having magnetic properties that are changed by the application of stress to the material,
  means for applying a steady magnetic field to said element,
  means for applying periodic pressures to said element at a frequency that is many times less than the frequency of said high frequency wave energy,
  and means coupled to said element for receiving electromagnetic wave energy radiated by said element.

6. The combination according to claim 5 including means for applying a static stress to said element.

7. The combination according to claim 5 wherein said means coupled to said element comprises a coupling loop having the plane thereof extending parallel to the direction of said applied field.

8. The combination according to claim 5 wherein said means coupled to said element comprises a resonator including a conductively bounded cavity surrounding said element.

9. A source of high frequency wave energy comprising
  an element of magnetic material having easy and hard axes of magnetization that are changed by the application of stress to the material,
  means for applying a magnetic field to said element at an acute angle to said easy axis,
  means for applying periodic pressure to said element along said hard axis,
  and means coupled to said element for receiving electromagnetic wave energy radiated by said element.

10. The combination according to claim 9 wherein said element is a sphere of yttrium iron garnet.

11. A source of high frequency wave energy comprising
  an element of antiferromagnetic material having an axis of antiparallel sublattice alignment,
  means for applying periodic pressure to said element in a direction normal to said axis,
  and means coupled to said element for receiving wave energy radiated by said element.

No references cited.