

Feb. 27, 1962

D. I. BOLEF ET AL

3,023,367

MASER

Filed May 29, 1957

2 Sheets-Sheet 1

Fig. 1.

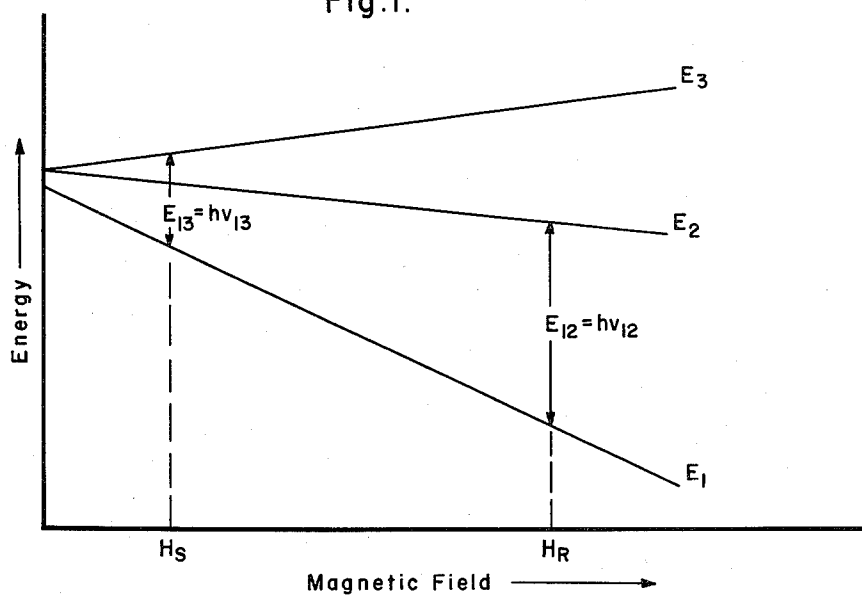
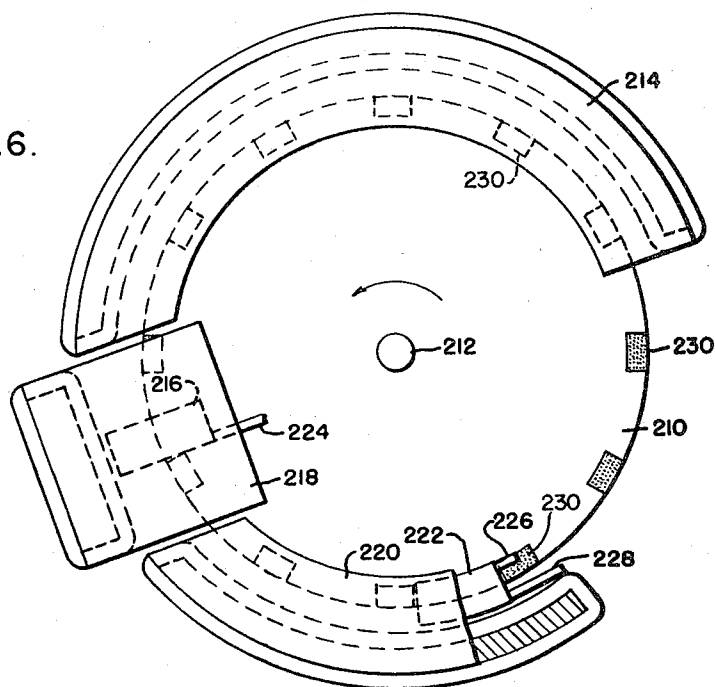


Fig. 6.



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2 Sheets-Sheet 2

Fig. 3.

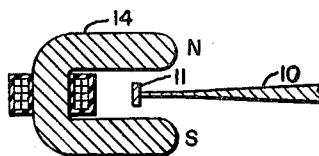


Fig. 2.

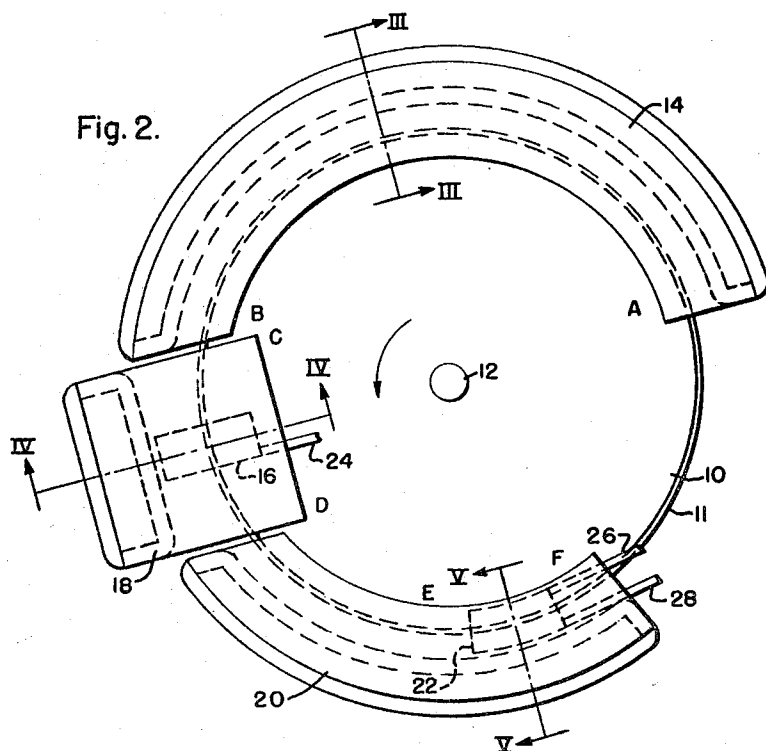


Fig. 4.

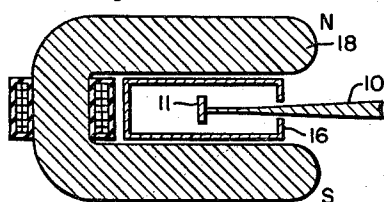
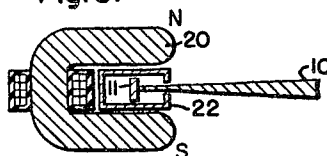


Fig. 5.



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3,023,367
MASER

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This invention relates to devices for amplifying or generating electromagnetic energy and, more particularly, to amplifying devices employing solids, liquids or gases for generating microwave energy by stimulated emission of radiation.

Generally speaking, "masers" may be defined as devices for amplifying or generating electromagnetic energy by utilizing molecules in the excited state of a microwave transition. Interaction between these excited molecules and a microwave field produces additional radiation and hence amplification by "stimulated emission."

The operation of masers such as the one described herein is dependent upon the fact that in certain paramagnetic materials a given electron may be in one of three or more different energy states. These energy states may be thought of as arising from the interaction of the electrons with internal or external fields. They may, therefore, be referred to as electron "spin states." An electron may undergo transitions between states as a result of interaction with external microwave energy of an appropriate frequency. In this respect, electrons in a low state may be transferred to a higher state when paramagnetic material under the influence of a magnetic field is subjected to a microwave field having a frequency corresponding to the energy difference between the two states. If the system of electrons is in a state of thermal equilibrium, corresponding to an excess electron population in the lower over the upper spin states, the paramagnetic material will absorb energy. When the situation is reversed, however, and there is an excess electron population in an upper state over a lower state, electrons in an upper state will release energy to incident microwave energy of the correct frequency, thereby producing amplification. If the frequency of the incident microwave energy is not of the correct frequency to be amplified, or if no signal is applied to the paramagnetic material, electrons in upper states by interaction with their surroundings, will revert to a lower energy level over a time interval called the "spin-lattice relaxation time."

It is an object of this invention to provide a new and improved maser for generating or amplifying electromagnetic energy.

Another object of the invention is to provide a solid state frequency converter.

A further object of the invention is to provide means for amplifying or generating electromagnetic wave energy by employing paramagnetic materials having at least three electron spin energy levels.

A still further object of the invention is to provide means for increasing the frequency at which a paramagnetic material will release electromagnetic energy.

Another object of the invention is to provide a solid state microwave frequency converter which operates superregeneratively.

The above and other objects and features of the invention will become apparent from the following detailed description taken in connection with the accompanying drawings which form a part of this specification and in which:

FIGURE 1 is a graphical illustration of three of the levels existing in a paramagnetic material showing how the levels change as a function of applied magnetic field;

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FIG. 2 is an illustration of one embodiment of the invention;

FIG. 3 is a cross-sectional view taken along line III—III of FIG. 2;

FIG. 4 is a cross-sectional view taken along the line IV—IV of FIG. 2 showing the first microwave cavity of the invention;

FIG. 5 is a cross-sectional view taken along line V—V of FIG. 2 showing the second microwave cavity of the invention; and

FIG. 6 is an illustration of another embodiment of the invention which operates superregeneratively.

Referring to FIG. 1, three energy levels of electrons in certain paramagnetic materials under the influence of a magnetic field H_0 are identified by the horizontal lines identified as E_1 , E_2 , and E_3 . It is apparent from the graph that the spacing between the energy levels varies as a function of a magnetic field applied to the paramagnetic material. Not all paramagnetic materials have three separate and distinct energy levels; however, examples of materials which do have three or more energy levels and are otherwise suitable for purposes of the present invention are:

(a) $Gd(C_2H_5SO_4)_3 \cdot 9D_2O$ (or $9H_2O$) diluted to one part in 200 with $La(C_2H_5SO_4)_3 \cdot 9D_2O$ (or $9H_2O$).

(b) $NiSiF_6 \cdot 6H_2O$ diluted 1:20 or more with

$ZnSiF_6 \cdot 6H_2O$

(c) Diluted chromium (Cr^{3+}) salts e.g.

$(NH_4)CR(SO_4)_2 \cdot 12H_2O$

or $CrK(SO_4)_2 \cdot 12H_2O$.

(d) Cr^{3+} in potassium cobalti-cyanide or in Al_2O_3 crystals or other host crystals.

Some of the electrons in the paramagnetic material will be in the lower energy state E_1 shown in FIG. 1 while the remainder will be in the higher energy states E_2 and E_3 . The paramagnetic material is in a normal or relaxed condition when the population distribution is such that there are more electrons in state E_1 than in state E_2 , and more electrons in state E_2 than in state E_3 . Electrons in the various energy states can interact with a microwave radiation field of appropriate frequency and either absorb energy from the radiation field while advancing to a state of greater energy or, under the influence of the radiation field, can give up some of their energy and drop to a state of lower energy. The amount of energy thus transferred is related to the frequency of the radiation field by the equation:

$$E_{upper} - E_{lower} = h\nu$$

where the symbol h is Planck's constant and ν is the frequency.

If an electron in the lower energy state E_1 is under the influence of a magnetic field H_0 , for example, and is subjected to a microwave field having a frequency corresponding to the energy difference between the states E_1 and E_2 , it will absorb energy and advance to the upper energy state E_2 . Similarly, if an electron in the lower energy state E_1 is under the influence of a magnetic field and is subjected to a microwave field having a frequency corresponding to the energy difference between states E_1 and E_3 , it will advance to the highest energy state E_3 . The energy increase is indicated in the drawing as $h\nu_{12}$. An electron in an upper state, on the other hand, may give up energy to a microwave field and drop to a lower state. The probability of transition up or down is the same. Therefore, whether a system of many electrons exhibits a net absorption or net emission of energy depends upon whether more electrons are in a lower or in an upper energy state. All such systems, when allowed to come to

thermal equilibrium, have more electrons in the lower energy states and, hence, are absorptive.

In order for the paramagnetic material to be emissive, there must be an excess of electrons in an upper energy state over that in a lower state. Thus, if there is an excess of electrons in energy state E_2 over state E_1 , the electrons in state E_2 can release energy and fall to energy state E_1 . Likewise, if there is an excess of electrons in energy state E_3 over states E_2 or E_1 the electrons in state E_3 will release energy while falling to one of the lower energy levels. In any event, before the paramagnetic material will release energy there must be an excess of electrons in an upper state over a lower state.

If a paramagnetic material under the influence of a magnetic field is subjected to a large enough microwave field having a frequency corresponding to the energy difference between states E_1 and E_3 , these states will become saturated, which means that the radiation field at a frequency corresponding to the energy difference between these two states completely overrides relaxation effects, and the two states become equally populated. This may result in a condition wherein there are more electrons in the energy level E_3 than there are in level E_2 . Thus, a steady state emissive condition is established between states E_3 and E_2 . If the paramagnetic material is now subjected to microwave energy having a frequency corresponding to the energy difference between states E_3 and E_2 , the electrons falling from state E_3 to state E_2 will release energy to the incident microwave field, thereby producing amplification. Under other conditions, depending upon the relaxation times between states E_3-E_2 and E_2-E_1 , the population in state E_2 can be made to exceed that in state E_1 , and stimulated emission will be possible at a frequency corresponding to the energy difference between states E_2 and E_1 .

If a paramagnetic material having three or more spin states is subjected to saturating microwave radiation under the influence of a low steady magnetic field H_S , then energy states E_1 and E_3 may become equally populated. Then, if the paramagnetic material is transported to a higher magnetic field H_R where stimulated emission is induced, the increase in field results in a corresponding increase in spacing between energy levels. Thus, three new energy levels now exist. This condition results in a corresponding increase in the frequency of emission between states E_3 and E_2 or between E_2 and E_1 . If the field H_R is high enough, the frequency of emission may exceed the frequency corresponding to the energy difference between states E_1 and E_3 in the low magnetic field H_S (i.e. the frequency of the saturating radiation). As shown in the drawing the frequency of emission V_{12} between states E_1 and E_2 at H_R is greater than the frequency V_{13} at H_S . It is, of course, necessary that the paramagnetic material be transported from the point where saturation occurs to the point where emission occurs in a time that is short compared with the spin-lattice relaxation time of the paramagnetic material.

One embodiment of the invention for effecting the process described above is shown in FIG. 2 and comprises a disc 10 of paramagnetic material, or containing some paramagnetic atoms or molecules, which is made to rotate about an axis 12. If preferred, only the periphery of disc 10 need be formed from paramagnetic material, or a hoop 11 of paramagnetic material may be affixed to the periphery of disc 10 as shown in FIGS. 3 to 5. A portion of the periphery of disc 10 rotates between the opposite poles of a magnet 14 for applying a steady magnetic field across the paramagnetic material. This has the effect of producing a thermal distribution of population among the energy levels. After passing through the field produced by magnet 14, the periphery of disc 10 passes through a resonant cavity 16 which is under the influence of a magnetic field H_S produced by magnet 18. Thereafter, the paramagnetic material passes between the opposite poles of a third magnet 20. At the end of magnet 20 is a sec-

ond resonant cavity 22 through which the periphery of disc 10 passes. Electromagnetic energy, of appropriate frequency, which will saturate the energy levels E_1 and E_3 of the paramagnetic material on disc 10 is fed to cavity 16 through waveguide 24 from a generator, not shown, to produce a standing wave condition within the cavity. Electromagnetic energy having a frequency different than the electromagnetic energy fed to cavity 16 may be fed into cavity 22 through waveguide 26 and will leave the cavity as amplified electromagnetic energy through the same waveguide or through waveguide 28. As shown by the polarity markings in FIGS. 3, 4 and 5, the magnetic fields produced by magnets 14, 18 and 20 are all in the same direction. It is, of course, necessary that the cavities 16 and 22 and the magnetic fields in which they are situated be tuned to the frequencies of the respective signals fed to waveguides 24 and 26.

In accordance with the description given above, the electromagnetic energy fed to cavity 16 through waveguide 24 has a frequency corresponding to the energy difference between the states E_1 and E_3 in field H_S . The magnetic field H_S produced by magnet 18 may be smaller than the magnetic field H_R produced by magnet 20. Furthermore, the magnitude of the field produced by magnet 20 determines the frequency at which stimulated emission will occur and this frequency, in turn, must be the frequency of the electromagnetic energy fed to cavity 22 through waveguide 26. It is, of course, necessary that the speed of rotation of disc 10 be such that the time taken to travel from cavity 16 to cavity 22 is less than the spin-lattice relaxation time so that the paramagnetic material is in an emissive condition when it reaches cavity 22.

It is to be understood that the rotating disc 10 is only one of several ways to transport the paramagnetic material through the various magnetic fields and resonant cavities. As an alternative, paramagnetic material may be placed on an endless tape which passes through elements corresponding to magnet 14, cavity 16, magnet 18, magnet 20 and cavity 22. A still further method would be to employ an inert fluid, containing the paramagnetic substance in solution or suspension which is circulated through tubes by a pump so that the electrons undergo the same process as in the mechanical arrangement described above. Liquid refrigerants such as liquid helium, hydrogen, argon, or nitrogen could be used as the fluids, thus combining spin transport and cooling functions. For a detailed description of the alternate devices described above, reference may be had to our copending application, Serial No. 656,093, filed April 30, 1957, and assigned to the assignee of the present application.

An embodiment of the invention which operates super-regeneratively is shown in FIG. 6. This embodiment of the invention is very similar to that shown in FIGS. 1 to 5 and comprises a disc 210 which rotates about an axis 212. A point on the periphery of the disc, as was the case with the embodiment shown in FIGS. 2 to 5, first passes through the magnetic field produced by magnet 214 and then passes to the resonant cavity 216 which is under the influence of a magnetic field produced by magnet 218. Electromagnetic energy of a frequency corresponding to energy difference between the states E_1 and E_3 is fed into cavity 216 through a waveguide 224 to produce a standing wave condition. After passing through cavity 216, the paramagnetic material passes to a magnet 220 and cavity 222 where incident electromagnetic energy entering waveguide 226 leaves as amplified electromagnetic energy through the same waveguide or through waveguide 228. As was the case with the embodiment of the invention shown in FIGS. 1 to 5, the magnetic field H_S produced by magnet 218 may be smaller than the magnetic field H_R produced by magnet 220.

The difference between the embodiments of the invention shown in FIGS. 2 and 6 is that in FIG. 6 the paramagnetic material is placed around the periphery of the rotating disc 210 in discrete and separate sections 230.

Sections 230 must be widely enough spaced so that only one can be in the cavity 222 at a given time. If the density of excited spins in any section is greater than that necessary to cause oscillation buildup in the cavity due to noise or incoming signal, the device can operate superregeneratively.

The separate sections 230 are moved through cavity 216 over a time interval which is long compared to the spin-spin relaxation time; while in cavity 216, they are subjected to the saturating microwave field which equalizes the electron spin population in states E_1 and E_3 . They are then transferred to cavity 222 where noise or incoming signal through waveguide 226 will cause oscillation buildup in the system. The superregenerative action involving quenching or a cutoff comes automatically because of the physical removal of the separate sections 230 from the cavity 222.

It is to be understood that in each of the embodiments of the invention shown and described above, it will usually be necessary, depending upon the paramagnetic material used, to operate the maser at a very low temperature. Accordingly, some means must usually be provided for subjecting the paramagnetic material to this low temperature during operation of the maser. The cooling system used in each case will, of course, depend on particular requirements.

It will be apparent that the device described herein could use a paramagnetic material having at least two electron spin levels in a magnetic field, and in which hyperfine interaction gives rise to further splitting of the electron energy levels. In this latter case, the frequency of the energy fed to the two cavities would have to be adjusted to that corresponding to the difference in energy between the levels in question.

Although the invention has been shown in connection with certain specific embodiments, it will be apparent to those skilled in the art that various changes in form and arrangement of parts may be made to suit requirements without departing from the spirit and scope of the invention.

We claim as our invention:

1. In apparatus for amplifying electromagnetic wave energy by stimulated emission of radiation, in combination, a continuous source of moving paramagnetic material moving in a predetermined path at a predetermined speed, said paramagnetic material having first, second and third discrete energy levels of electrons, said second level being higher than said first level, said third level being higher than said second level, the separation between said energy levels being dependent upon the magnitude of an external magnetic field applied to the paramagnetic material, first and second spaced resonant cavities located in predetermined position with respect to said path and through which the source of paramagnetic material passes as it moves along said path, means adjacent the first resonant cavity for subjecting the paramagnetic material to a first magnetic field of predetermined direction and of a predetermined first magnitude while the paramagnetic material is in the first resonant cavity, means for continuously feeding electromagnetic wave energy of a first predetermined frequency and of at least a predetermined amplitude to said first resonant cavity, the spacing between the first energy level and the third energy level being such that the electrons in said paramagnetic material while in said first resonant cavity undergo transitions between said first energy level and said third energy level while subjected to electromagnetic wave energy of said first frequency and to the first magnetic field of said first magnitude, said predetermined speed being such that the movement of the paramagnetic material from the first resonant cavity to the second resonant cavity is short compared to the spin-lattice relaxation time of electrons between the third energy level and the second energy level, means adjacent the second resonant cavity for sub-

jecting the paramagnetic material to a second magnetic field of a second predetermined magnitude greater in magnitude than the first magnetic field and having a direction substantially parallel to the direction of the first magnetic field as the paramagnetic material passes through the second resonant cavity, the spacing between the second and third energy levels in the second resonant cavity being greater than the spacing between the first and third energy levels in the first resonant cavity, and means for conducting electromagnetic wave energy of a second predetermined frequency to be amplified to and from the second resonant cavity, the second frequency corresponding to the transition frequency between the third and second energy levels at said second magnetic field magnitude whereby electrons in the third energy level give up energy to the electromagnetic wave of said second frequency as they revert to the second energy level thereby amplifying the wave energy of second frequency, the total length of said predetermined path and said predetermined speed being chosen with respect to each other and the paramagnetic material whereby paramagnetic material after leaving the second resonant cavity traverses a portion of at least a predetermined length of the path in returning to the first resonant cavity, the last-named paramagnetic material remaining in said portion at least a sufficient time to substantially produce a thermal distribution of the electron population between the energy levels.

2. In apparatus for amplifying electromagnetic wave energy by stimulated emission of radiation, in combination, a continuous source of moving paramagnetic material moving in a predetermined path of a predetermined speed, said paramagnetic material having first, second and third discrete energy levels of electrons, said second level being higher than said first level, said third level being higher than said second level, the separation between said energy levels being proportional to the strength of an external magnetic field applied to the paramagnetic material, first and second spaced resonant cavities through which the paramagnetic material passes as it moves along said path, means disposed adjacent the first resonant cavity for subjecting the paramagnetic material to a first magnetic field of a first predetermined magnitude and direction as it passes through the first resonant cavity, means for continuously feeding electromagnetic wave energy to said first resonant cavity of at least a predetermined amplitude and having a first predetermined frequency, the spacing between the first energy level and the third energy level being such that the electrons in said paramagnetic material while in said first resonant cavity under go transitions between said first energy level and said third energy level whereby an excess of electrons is created in the third energy level, relaxation of electrons from the third energy level to the second energy level producing an excess of electrons occupying the second energy level, the speed of movement of the source being such that the paramagnetic material is transferred from the first resonant cavity to the second resonant cavity in a time which is short compared to the spin-lattice relaxation time between the second and first energy levels, means adjacent the second resonant cavity for subjecting the paramagnetic material to a second magnetic field of a second magnitude greater in magnitude than that of the first magnetic field as the paramagnetic material passes through the second resonant cavity, the direction of the second magnetic field being substantially parallel to that of the first magnetic field, the magnitude of the second magnetic field being sufficiently large that the spacing between the second and first energy levels in the second resonant cavity is greater than the spacing between the first and third energy levels in the first resonant cavity, and means for conducting electromagnetic wave energy of a second frequency higher than said first frequency to and from said second resonant cavity, the electrons of said

paramagnetic material while in the second resonant cavity having transitions between the second and first energy levels at said second frequency and second magnetic field magnitude, at least some of the electrons in the second energy level while the paramagnetic material is in the second resonant cavity reverting to the first energy level and giving up energy to the electromagnetic wave energy of said second frequency thereby amplifying said last-named electromagnetic wave energy, the total length of said predetermined path and said predetermined speed being chosen with respect to each other and the paramagnetic material whereby paramagnetic material after leaving the second resonant cavity traverses a portion of at least a predetermined length of the path in returning to the first resonant cavity, the last-named paramagnetic material remaining in said portion at least a sufficient time to substantially produce a thermal distribution of the electron population between the energy levels.

3. In apparatus for superregeneratively amplifying electromagnetic wave energy by stimulated emission of radiation, in combination, a continuous source of a moving material moving in a predetermined path at a predetermined speed, discrete similar sections of a paramagnetic material carried at substantially equally spaced intervals by said moving material, said paramagnetic material having three discrete levels of electrons including an upper level, a lower level, and an intermediate level, the separation between said energy levels being proportional to the strength of an external magnetic field applied to the paramagnetic material, first and second spaced resonant cavities through which the paramagnetic sections pass as the moving material moves along said path, first magnetic field producing means disposed in predetermined position with respect to the first resonant cavity for subjecting the sections of paramagnetic material carried by the moving material to a transverse magnetic field of predetermined direction and of a first magnitude as the sections move into position within the first resonant cavity, means for feeding electromagnetic wave energy of a predetermined first frequency and of at least a predetermined amplitude into said first resonant cavity at least during the time intervals during which any substantial portion of a discrete section of paramagnetic material is within the first resonant cavity, the spacing between a pair of energy levels comprising the lower energy level and the upper energy level while said discrete section of paramagnetic material is in said first magnetic field being such that transitions of electrons occur between the pair of levels comprising the lower energy level and the upper energy level thereby creating an excess of electrons having high energy spin states and occupying the upper energy level, means adjacent the second resonant cavity for subjecting the discrete section of paramagnetic material to a second magnetic field which is greater in magnitude than the first magnetic field as the section of paramagnetic material passes through the second resonant cavity, the direction of the second magnetic field being substantially parallel to that of the first magnetic field, and means for conducting an electromagnetic wave energy signal of a second predetermined frequency to and from the second resonant cavity, the second magnetic field being sufficiently greater in magnitude than the first magnetic field whereby the separation between energy levels of a different pair of levels is greater while the paramagnetic material is in the second resonant cavity than the separation between

the first named pair of energy levels while the paramagnetic material is in the first resonant cavity, said different pair including one of the energy levels of the first named pair, the electrons of said paramagnetic material having transitions between said different pair of energy levels at said second frequency while in said second magnetic field of greater magnitude, the speed of movement of said paramagnetic section with respect to the spin-lattice relaxation times of electrons between said three energy levels being such that at least some of the electrons in the discrete paramagnetic section in the second resonant cavity give up energy to the electromagnetic wave of said second frequency before spin-lattice relaxation is complete in the paramagnetic material of the last named section, the density of the electrons with high energy spin states in the discrete paramagnetic section and occupying the upper level of said different pair of levels being greater than that necessary to cause oscillation build-up in the second resonant cavity due to noise and a signal of said second frequency, said speed of movement of the continuously moving material being preselected whereby said last named discrete section of paramagnetic material moves out of the second resonant cavity after a predetermined time interval to provide for damping of electromagnetic wave energy developed in said second cavity while the discrete section was disposed therein, the build-up of energy in the second resonant cavity as discrete sections of paramagnetic material move through the second cavity providing for superregenerative pulsed amplification of the signal of said second frequency, the total length of said predetermined path and said predetermined speed being chosen with respect to each other and the paramagnetic material whereby a discrete paramagnetic section after leaving the second resonant cavity traverses a portion of at least a predetermined length of the path in returning to the first resonant cavity, the last-named discrete paramagnetic section remaining in said portion at least a sufficient time to substantially produce a thermal distribution of the electron population between the energy levels therein.

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