Nov. 29, 1960 D. I. BOLEF ET AL 2,962,585

SUPERREGENERATIVE MASER

Filed June 20, 1957 2 Sheets-Sheet 1

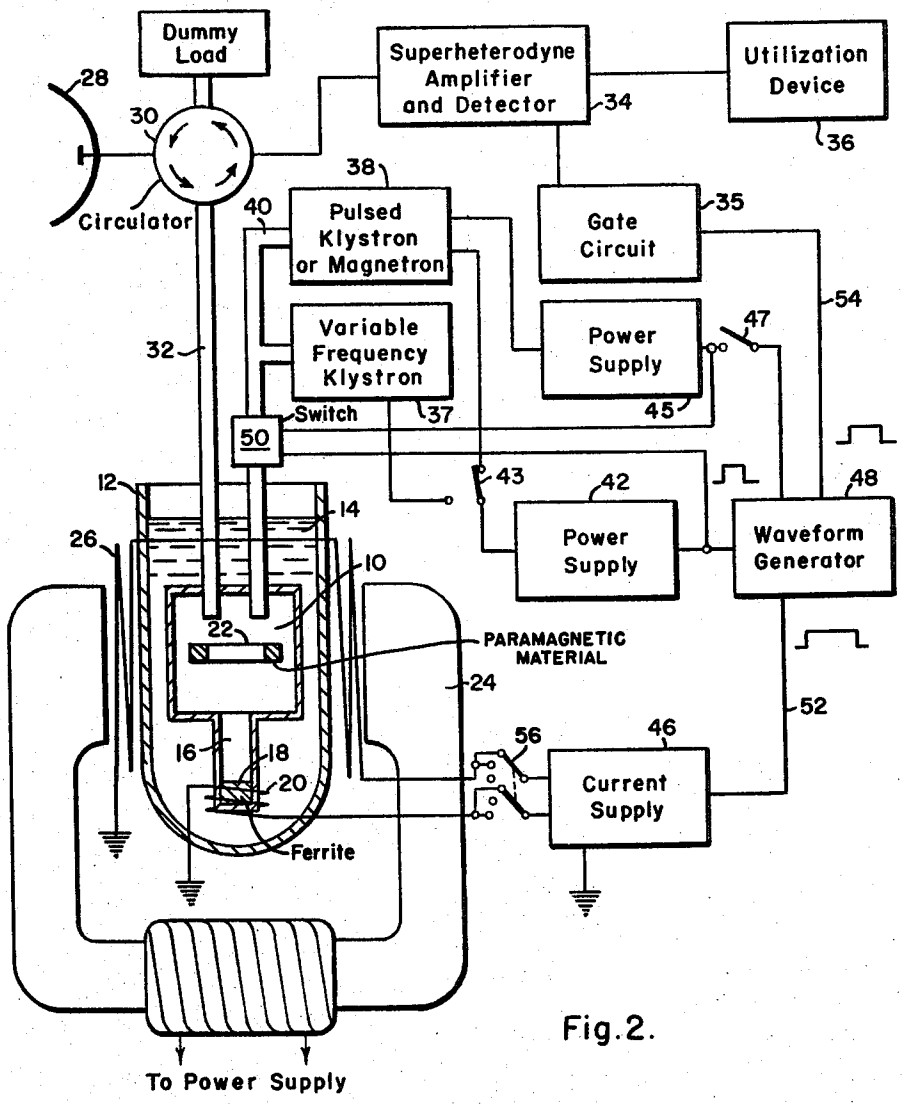


Fig. 2.

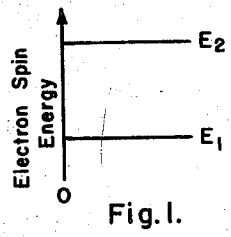


Fig. 1.

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SUPERREGENERATIVE MASER

Filed June 20, 1957 2 Sheets-Sheet 2

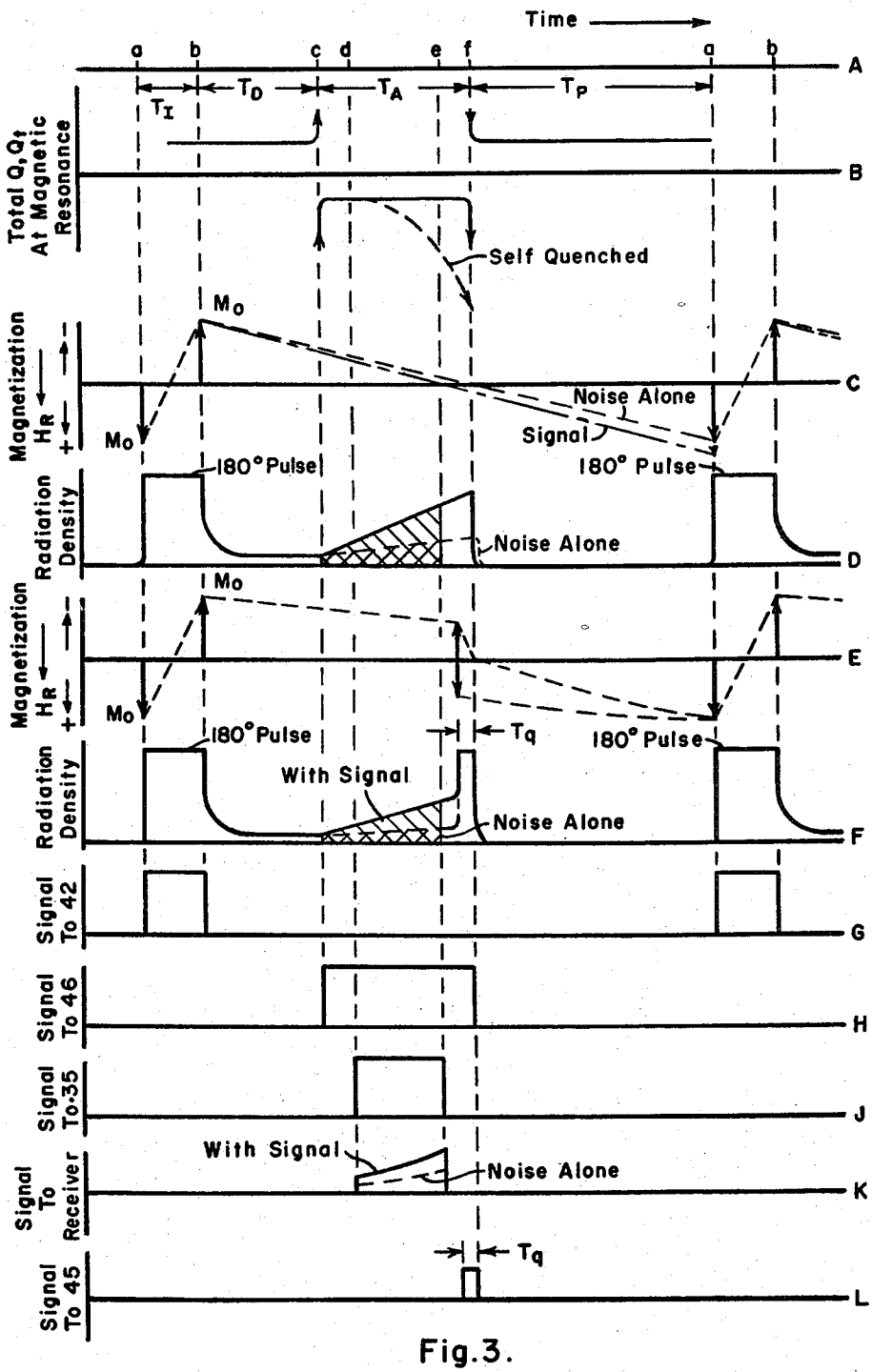


Fig.3.

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2,962,585

SUPERREGENERATIVE MASER

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11 Claims. (Cl. 250—20)

This invention relates to devices employing solids, liquids or gases for amplifying or generating electromagnetic energy, and more particularly to a solid state maser which operates superregeneratively to improve gain characteristics and to enable higher working temperatures to be used.

Generally speaking, "masers" may be defined as devices for amplifying or generating electromagnetic energy by utilizing molecules in an excited state. Interaction between these excited molecules and an electromagnetic 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 paramagnetic materials the electrons may be in different energy states. These states may be thought of as arising from the interaction of the magnetic moments (associated with spins) of the electrons with internal or external fields. We may therefore refer to them as electron "spin states." The energies of these electron spin states may be varied by an external magnetic field; and the energy difference between two given electron spin states is, in part, determined by the magnitude of this external magnetic field.

If a paramagnetic material having an excess electron spin population in the lower of two energy states is exposed to a pulse of electromagnetic power on resonance of appropriate strength and duration, electrons originally in the lower state will be raised to the upper state while those in the upper state will be transferred to the lower state. Thus, such a pulse transforms an excess population in the lower state to an excess population in the upper state. The pulse of electromagnetic energy inverts the distribution of the electrons, and the process by which this inversion occurs is called the "180° pulse method."

The population of the energy levels of electrons in a paramagnetic material may also be inverted by a process called "adiabatic rapid passage." In this process electrons in the paramagnetic material are subjected to an electromagnetic field of constant frequency while, at the same time, they are subjected to a varying magnetic field so that the magnetic field corresponding to resonance at the microwave frequency to which the paramagnetic material is subjected is traversed once. Thus, the magnetic field which is initially far off resonance is swept continuously through the value required for resonance and then far off resonance on the other side. If the conditions are met for adiabatic rapid passage, the populations of the two electron energy states are inverted as they are in the case of the 180° pulse method. An alternative form of adiabatic rapid passage employs a constant magnetic field. In this latter process, the paramagnetic material is subjected to an electromagnetic field which varies in frequency whereby the frequency is swept from a value on one side of resonance to a value on the other side of resonance.

If a paramagnetic material having an excess electron population in the upper energy state produced by one

of the processes described above is placed in a resonant cavity situated in a magnetic field of the correct magnitude, and if electromagnetic energy of proper frequency is fed into the cavity, the electrons in the higher energy state will revert to the lower energy state, thereby releasing energy which produces an effect corresponding to amplification of the original electromagnetic energy fed into the cavity. In order to release the energy of the electrons in the upper state to produce amplification, however, the original signal fed into the cavity must be of an appropriate frequency which is determined by the difference in the energy levels of the electrons in the upper and lower states; and this energy difference is, in turn, dependent upon the strength of the external magnetic field applied to the paramagnetic material. Thus, by varying the strength of this external magnetic field, the frequency at which the paramagnetic material will release its energy in the resonant cavity may be varied also. If the frequency of the signal fed into the cavity is not of the correct frequency to be amplified, or if no signal is introduced at all, the electrons in the upper energy state, by interaction with this surroundings, will revert to the lower energy level over a time interval called the "spin-lattice relaxation time."

If a solid state maser amplifier of the type described above is operated at liquid helium temperatures, it may have a noise figure as low as 0.04 db. If use is is to be made of this low noise figure without coupling masers in series, it is necessary for the maser to have a high enough gain to connect into a conventional receiver. Since noise figures for the latter are commonly greater than 6 db, a gain of 25 db or more will be required in the maser.

In order to increase the gain of a maser, it is usually operated regeneratively wherein the figure of merit or quality factor Q_m of the paramagnetic material in the resonant cavity is made negative, but not numerically smaller than Q_c, the loaded cavity Q, the principle being similar to that of a conventional regenerative amplifier employing positive feedback. "Q" is the figure of merit or quality factor, and is defined generally as the ratio of the reactance of an element to the equivalent series resistance, the reactance providing for energy storage, and the equivalent series resistance resulting in energy dissipation or loss. In accordance with established custom and usage in the electical engineering arts which provide for the calculation and designation of circuit Q's for series and parallel resonant circuits, as aforementioned, the resonant cavity is considered as having a cavity quality factor Q_c. The "Q" of the paramagnetic material employed herein and utilizing an electron spin system involving two energy levels is negative when the net rate of emission of energy from higher level to lower level is greater than the net rate of absorption. This occurs when the spin population of the upper level is greater than that of the lower level. The manners in which this condition is created in apparatus embodying this invention are set forth in detail hereinafter. As aforementioned, the quality factor of the paramagnetic material is designated herein as Q_m. The total or effective cavity Q, Q_t, must satisfy the following equation:

$$\frac{1}{Q_t}=\frac{1}{Q_m}+\frac{1}{Q_c}$$

In principle, a regenerative maser, where Q_t is positive but large, is capable of unlimited gain. In practice, however, considerations of gain stability and gain dependence on signal strength set an upper limit to the realizable gain. That is, as in all regenerative amplifiers, the amount of feedback, or the value of negative Q_m, is critical so that a slight change in conditions may cause the device to break into oscillation.

It is an object of this invention to provide a maser capable of improved gain over that available in a regenerative maser while at the same time avoiding the undesirable characteristics of regenerative operation.

More specifically, an object of the invention is to provide a means for operation of a superregenerative maser wherein the total quality factor Q_t of a resonant cavity together with the paramagnetic material which it contains is periodically allowed to become negative by a suitable change in the loaded quality factor, Q_c, of the cavity. In this manner, as in conventional superregenerative amplifiers, the instability of regenerative operation is avoided, and the gain of the maser can be greatly increased for practical applications.

A further object of the invention is to provide a new and improved superregenerative maser wherein the total quality factor Q_t is shifted between a positive and negative value by shifting the strength of a magnetic field applied to paramagnetic material.

Still a further object is to provide new and improved means for quenching a superregenerative maser.

Finally, a more general object of the invention is to provide a new and improved device employing solids, liquids or gases for achieving amplification of electromagnetic energy by stimulated emission of radiation.

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 two of the energy levels of an electron in a paramagnetic material;

Fig. 2 is an illustration of one embodiment of the invention which operates superregeneratively; and

Figs. 3A–3L are a series of curves, all on the same time axis, which illustrate the operation of the invention shown in Fig. 2.

Referring to Fig. 1, two of the energy levels of an electron in a paramagnettic material situated in a magnetic field are indicated by the horizontal lines identified as E_1 and E_2. Some of the electrons in the paramagnetic material will be in the lower energy state E_1 while others will be in the higher energy state E_2. The paramagnetic material is in a normal or relaxed condition when there is an excess electron population in the lower energy state E_1 over that in the upper energy state E_2. Electrons in the energy states E_1 and E_2 can interact with an electromagnetic 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 (i.e., E_2-E_1) is related to the frequency of the radiation field by the equation:

$$E_2-E_1=h\nu$$

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

If an electron in the lower energy state E_1 is situated in an electromagnetic field of proper frequency and polarization, it will absorb energy and rise to the upper energy state E_2. An electron in the upper state, on the other hand, will give up energy to the electromagnetic field while dropping to the lower state. The probability of either transition is the same. Therefore, whether a system of many electrons exhibits a net absorption or emission of energy depends upon whether more electrons are in the lower or upper energy state. All such systems when allowed to come to thermal equilibrium (i.e., are relaxed) have more electrons in the lower energy state E_1 than in E_2, and, hence, are absorptive.

In order for the paramagnetic material to be emissive and release energy, there must be an excess electron population in the upper energy state E_2. An excess population in the upper state may be produced by the 180° pulse method which operates in the following way: First, a magnetic field H_R is applied across the paramagnetic material to provide a means of varying the energy difference between the electron spin states. After a time determined by the spin-lattice relaxation time, an excess electron population exists in the lower state. Then, if the paramagnetic material with an excess population in the lower state is subjected to a pulse of electromagnetic power on resonance and of proper strength, duration and polarization, the electrons originally in the lower state will be raised to the upper state and vice versa so that now an excess electron population exists in the upper state. By "on resonance," it is meant that the frequency of the electromagnetic power pulse must be that corresponding to the difference in energy between states E_1 and E_2. That is, the frequency ν of the microwave power must satisfy the equation

$$\nu=\frac{E_2-E_1}{h}$$

where h is again Planck's constant. If paramagnetic material situated in a resonant cavity having an excess electron population in the upper state is now subjected to electromagnetic energy of proper frequency and polarization, the excess electron population in the upper state will release its energy to the incident electromagnetic wave, thus amplifying it. In all cases, the time between inversion of spin populations and the release of energy for amplification purposes must be less than the spin-lattice relaxation time. That is, amplification must take place before the electrons inherently revert to their original energy levels. The spin-lattice relaxation time may be increased considerably by lowering the temperature of the paramagnetic material to that of liquid helium or some other suitable refrigerant. Consequently, the operational cycle of a maser may be increased in time considerably by refrigerating the paramagnetic material.

As an alternative method for producing amplification, the paramagnetic material in the resonant cavity under the influence of constant magnetic field may be subjected to electromagnetic energy of varying frequency so that the frequency is changed from a value on one side of the resonant frequency given by the equation

$$\nu=\frac{E_2-E_1}{h}$$

to a value on the other side of resonance. As an alternative, the electromagnetic energy may be of constant frequency; and the applied magnetic field may be varied. By either of these processes, the populations of the energy levels E_1 and E_2 will be inverted by adiabatic rapid passage. Thereafter, electromagnetic energy fed into the cavity may be amplified exactly as described in the preceding paragraph in connection with the 180° pulse method.

As was explained in the introductory part of this specification, the gain of a maser may be increased considerably by superregenerative operation (i.e., allowing the total quality factor Q_t of a resonant cavity together with the paramagnetic material it contains to become negative).

The time sequence of all superregenerative masers will have the same basic features. These features are shown in Fig. 3A. During the entire cycle the paramagnetic material is subjected to an external magnetic field H_R. The time sequence starts at time a with the spin system in approximate thermal equilibrium wherein there is an excess electron population in state E_1 over E_2. During the first period T_I, from a to b, the electron populations in levels E_1 and E_2 are inverted by either the 180° pulse method or by adiabatic rapid passage, both of which were described above. The signal to be amplified should be present in the cavity at time c.

During the next period T_D from b to c, the radiation in the cavity containing paramagnetic material is allowed to decay to a value less than the signal to be detected.

This radiation consists of the ringing of the cavity after the inverting radiation and also the radiation due to spontaneous coherent emission from the spin system. At the start of the next period T_A, from *c* to *f*, the system is allowed to become unstable by a change in Q_c so as to make Q_t negative, and oscillation starts to build up. For the duration of this period (i.e., up until time *f*, as shown in Fig. 3B, the cavity quality factor, Q_c, is maintained at the high value so that Q_t remains negative and oscillation takes place. For part of this period, namely between *d* and *e*, the receiver is made sensitive by a gating pulse so as to accept the radiation from the cavity only during time *d* to *e*. Gating of the receiver may be dispensed with if desired. Then, after the active period, T_A, there follows a period T_P from *f* to *a*, during which the spin system is again prepared for inversion. That is, during this time the spin system is again brought into approximate thermal equilibrium. At *a* the cycle is again repeated.

The preparation of the system to bring it back to approximate thermal equilibrium after the active period T_A, may be effected in one of several ways. One of these ways is to permit self-quenching (i.e., to allow Q_m to become positive again because of spin-lattice relaxation). This method is shown in Figs. 3C and 3D. In Fig. 3C, it can be seen that at the start of the cycle the excess spin population at the lower energy level E_1 is represented by an electron magnetization M_0 (which is not necessarily the equilibrium magnetization) lined up parallel to an external magnetic field H_R applied to the paramagnetic material. At *a*, as shown in Fig. 3D, a 180° pulse of proper frequency and duration is applied to the paramagnetic material. Its effect is to rotate the spin magnetization M_0 through 180° and to establish an emissive state. That is, the 180° pulse inverts the populations of the electron energy levels E_1 and E_2 between *a* and *b*. During this time and up until *c*, the total quality factor Q_t cannot be allowed to become negative because of the presence of radiation in the form of the pulse tail and radiation due to spontaneous coherent emission, either of which could trigger an oscillation. By time *c* such radiations will have died away to a value comparable with thermal noise and at this time Q_t can be made negative by a change in Q_c, as shown in Fig. 3B. From *c* oscillations will build up at a rate governed by the value of Q_t, the amplitude of which is proportional to the radiation present in the cavity at *c*. Because of the decrease in value of magnetization as shown in Fig. 3C, however, the buildup will not be exactly exponential with time. Between *d* and *e* electromagnetic energy from the cavity is accepted by a receiver or other utilization device so that the output from the receiver or device will be a pulse, shown shaded in the figure, whose height or area will be related to the signal (or noise) present in the cavity at *c*. At *f* (sooner in the presence of a signal) the value of magnetization M will have fallen to zero. Since Q_t will by then be positive again (due to the decrease in M), the radiation in the cavity will die away. During the period T_p the value of M grows in the positive direction and at *a* has again attained its original value or a slightly greater value if a signal has been amplified during the cycle.

Another form of operation called "external quench by second inversion," is to re-invert whatever magnetization remains after T_A so as to help the thermalization process. This may be achieved by a second 180° pulse or a second adiabatic rapid passage between times *e* and *f*.

The characteristic of either of these forms of operation is that in a given cycle the gain depends upon the value of M_0 at the start of the cycle. This, in turn, depends slightly on the magnitude of the signal received in the previous cycle. Gain variation may be minimized by reducing the bandwidth of the device so that it will be insensitive to small changes in signal occurring with a frequency greater than a small submultiple of the reception frequency. As a "yes-no" detector, the device would work well and has the advantage of extreme simplicity coupled with very high gain.

The disadvantage described above in the "self-quenched" and "quenched by second inversion" cases of gain variation from cycle to cycle may be overcome if M_0 has the same value at the start of each cycle. One method of achieving this is to reduce M to zero by an external electromagnetic pulse at a definite time in each cycle. This external quench method is shown graphically in Figs. 3E and 3F, between *e* and *f*. As shown in Fig. 3F, a quench pulse of duration T_q is applied. This pulse may take the form of a 90° pulse (i.e., a modified 180° pulse of half the normal duration or an extended pulse of electromagnetic energy at resonance so as to "saturate" the levels E_1 or E_2 of the paramagnetic material). Either method has the effect of equalizing the electron populations in states E_1 and E_2 at time *f* so that the magnetization after T_p is always the same whatever the signal strength. A second method applicable in certain materials is to employ a strong light pulse to return the spin population to thermal equilibrium in a very short time. Still another method is to dope the material with a paramagnetic ion having a very short T, and a transition which can be made degenerate with that of the working substance by a small change in magnetic field. Thermal equilibrium is then achieved in a very short time. In the first of the cases described above, the effect is to reduce the magnetization M to zero as shown in Fig. 3E. Then, because the interval between *f* and *a* is fixed, and the same for each cycle, M_0 has the same value at the start of each cycle. The gain of this device is then constant with time. Other aspects of the action are identical with those of the internally quenched type shown in connection with Figs. 3C and 3D.

One embodiment of the invention for superregeneratively amplifying electromagnetic energy is shown in Fig. 2 and comprises a microwave cavity **10** which is situated in a vessel **12** containing liquid helium **14** or some other suitable refrigerent. As will be understood, the cavity **10** is air-tight whereby the liquid helium surrounds the outside of the cavity **10** only. The cavity **10** has coupled to it an element **16** containing a ferrite material **18**. Surrounding the ferrite material **18** is a coil **20**, the purpose of which will hereinafter be described.

Within cavity **10** is situated a sample **22** of paramagnetic material. Although shown as a ring, the paramagnetic material may take any form which is found best for a particular application and may even be affixed to the inner walls of the cavity **10**. For an electromagnetic wave generator of reasonable power output, it is desirable to use a paramagnetic material **22** with the largest electron spin density consistent with a line width less than 10 gausses. At the present time heavily doped silicon (up to 10^{20} donors/cc.), diphenyl-picryl-hydrazyl (10^{21} spins/cc.), or diluted potassium chromicyanide (10^{20} spins/cc.) will prove to be among the materials suitable for this application. It will be understood, however, that the paramagnetic material need not necessarily be in the solid state but may take the form of a liquid or a gas.

The paramagnetic material contained in the resonant cavity is subjected to an external magnetic field H_R produced by electromagnet **24**. This magnet provides the necessary external magnetic field to establish or partially determine an energy difference between the electron spin states E_1 and E_2. Also surrounding the vessel **12** and cavity **10** is a Helmholtz coil **26** which produces a magnetic field across the paramagnetic material **22** which is in the same direction as that produced by magnet **24**. This field may be used in changing the value of Q_t in a manner hereinafter described.

Electromagnetic energy received by an antenna **28**, for example, is fed through a ferrite circular **30** and waveguide **32** into the cavity **10**. This, then, constitutes the electromagnetic energy which is to be amplified by the

maser. The circulator 30, well known in the art, will permit the signal from antenna 28 to reach cavity 10 and will permit the amplified signal from the cavity to reach a superheterodyne amplifier and detector 34, but it will not permit noise from circuit 34 to reach the cavity 10. The amplified signal from the maser, after passing through circuit 34, is then applied to a display device 36 or other similar utilization apparatus. In the case of radar apparatus, the display device will usually take the form of a cathode ray tube.

Electromagnetic energy for achieving electron population inversion by the 180° pulse method is supplied from a pulsed klystron or magnetron 38, the energy being fed to cavity 10 through waveguide 40. If it is desired to employ adiabatic rapid passage to invert the populations of the levels in the paramagnetic material 22, the output of a variable frequency klystron 37 is applied to cavity 10 through waveguide 40 or the magnetic field may be swept by means of the Helmholtz coils 26. The klystrons 37 and 38 are, in turn, controlled through a high voltage power supply 42, the output of the power supply being applied to one or the other of the klystrons through switch device 43.

The klystron or magnetron 38 may also be triggered through a second power supply 45 when switch 47 is closed. This latter klystron is employed to supply a 90° quench pulse or a second inverting pulse to the cavity 10 in a manner hereinafter described. The superheterodyne amplifier and detector 34 are gated on and off by the output of a gate circuit 35, substantially as shown. The Helmholtz coil 26 and the coil surrounding the ferrite 18 are periodically supplied with current as required from a current supply 46 in accordance with the setting of switch 56 and the control waveform from waveform generator 48.

The gate circuit 35, klystrons 37, 38 and current supply 46 are each energized during a portion of each cycle of the maser by output signals derived from a complex waveform generator 48. This waveform generator 48 may take the form of a generator which produces several output waveforms consisting of pulses spaced in time of various amplitudes and shapes. Since waveform generators of this type are well known in the art, a detailed description of the same is not given herein.

Operation of the invention may best be understood by reference to Figs. 3G–3K taken in connection with Figs. 3A–3F. In Fig. 3G the output of power supply 42 as applied to klystron 38 is shown. Thus, it can be seen that the supply applies a voltage pulse to klystron 38 during the period T_I to enable it to supply a pulse of electromagnetic energy to the paramagnetic material within cavity 10 and thereby invert the populations of electron energy states E_1 and E_2 by the 180° pulse method. If adiabatic rapid passage is employed, switch device 43 connects klystron 37 to power supply 42 to apply a variable frequency sweep of electromagnetic energy to the cavity 10. At *b* in the cycle, therefore, the electron energy levels are inverted so that now an excess electron spin population is in the upper energy level. From point *b* to point *c* the radiation in the cavity is allowed to decay in the manner described above and klystrons are quiescent. To prevent noise or power from 37 or 38 reaching 10 during T_A, it is necessary to have a refrigerator ferrite switch 50 as indicated in Fig. 2 between 37, 38 and 10. This switch is opened by the pulse from generator 48 applied to circuit 42 or 45 only when klystron power need be applied to 10 (i.e., during T_I and T_q). Then, at point c (Fig. 3H) an output pulse from waveform generator 48 on lead 52 will trigger current supply 46 to apply current to coil 20 surrounding the ferrite element 18 and/or the Helmholtz coil 26. This has the effect in the ferrite case of changing the loading on the cavity so that Q_c becomes larger than $-Q_m$ and in the Helmholtz coil case of bringing the paramagnetic resonance frequency into exact coincidence with cavity resonance with the same result. Thus, the total quality factor Q_t, of the cavity, together with the paramagnetic material, becomes negative. At point *d* in the cycle a signal from waveform generator 48 on lead 54 (Fig. 3J) will cause gate circuit 35 to energize superheterodyne amplifier and detector 34 and permit them to pass the amplified output of the maser on to the utilization device 36. The signal from waveform generator 48 applied to lead 54 persists until *e* in the cycle at which time the amplifier and detector 34 are gated off. Thus, between *d* and *e* the signal appearing in Fig. 3K will be applied to the utilization device 36.

At time *f* the value of Q_t is made positive again by means of either 18 or 26. This in itself would quench oscillation without, however, affecting M.

Assuming that external quenching of the maser is employed, waveform generator 48 will apply a pulse shown in Fig. 3L starting at some time between points *e* and *f* to power supply 45 through switch 47 to cause klystron 38 to apply a pulse of power to cavity 10. This, then, has the effect of returning the paramagnetic material 22 either to zero or to a value approaching thermal equilibrium in accordance with the explanation given above. At the expiration of time T_q it will, of course, be understood that the waveform generator 48 again cuts off klystron 38. In these cases between *f* and *a*, during the period T_P, the system is being prepared through spin-lattice relaxation for the next cycle of operation. The doping plus field switching methods mentioned above as well as being effective means of preparing the system are also very good quenching methods.

It can thus be seen that we have disclosed a superregenerative maser which has inherently both high gain and high linear output in comparison with a similar maser operated regeneratively. Although we have shown the invention in connection with a certain specific embodiment, it will be readily 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. It will also be understood that if adiabatic rapid passage is employed to invert the population of the electron energy levels, the frequency of the signal fed through waveguide 40 may be made constant (by employing klystron 38) and by varying the current through the coil of magnet 24 or of coil 26 to sweep the applied external magnetic field through resonance.

The superregenerative mode of operation is possible over a wide range of frequency from radio frequencies, through microwaves up into the far infrared.

To summarize the advantages offered by the apparatus and method of the instant invention as disclosed hereinabove, two new methods of initiating oscillation buildup in a superregenerative maser have been disclosed, these being Q switching of the cavity Q to a high value to thereby make the total Q negative, and magnetic field shifting which brings the paramagnetic resonance frequency into exact coincidence with the cavity resonance frequency. Buildup is stopped by complementary procedures of decreasing the cavity Q, and shifting the magnetic field back to its former value.

In addition, new and improved methods of increasing the repetition rate of superregenerative maser apparatus have been disclosed by providing positive damping, and these include the use of a 90° damping pulse or quenching pulse, a 180° pulse, or an extended quenching pulse, and doping plus magnetic field change. As was pointed out hereinbefore, where self-quenching takes place, the time required for restoration of the apparatus to a condition suitable for repeating the cycle of operation may be considerably longer than the time required where positive quenching as taught in the instant application is provided. Furthermore, a new and improved apparatus and method are disclosed for increasing the repetition rate of a superregenerative maser and at the same time maintaining the gain of the maser apparatus constant from

cycle to cycle by utilizing a quenching pulse, as explained in more detail hereinbefore.

We claim as our invention:

1. Apparatus for superregeneratively amplifying electromagnetic energy comprising, in combination, a resonant cavity, paramagnetic material positioned within said cavity, means for subjecting said paramagnetic material to a magnetic field, means for feeding pulses of electromagnetic energy to said cavity to effect electron spin state preparation in said paramagnetic material, said pulses having a frequency corresponding to the energy difference between two electron energy levels in said paramagnetic material, means for feeding electromagnetic energy of signal frequency into said cavity and for conveying amplified electromagnetic energy from the cavity, and means for periodically changing the quality factor Q_c of said cavity to thereby change the total quality factor Q_t to a negative value to permit the buildup of oscillations of said signal frequency and thereafter restoring the cavity quality factor Q_c to substantially its original value to change to total quality factor Q_t to a positive value and quench said oscillations, the periodic buildup and subsequent quenching of oscillations in said cavity providing for superregenerative amplification.

2. Apparatus for superregeneratively amplifying electromagnetic signal energy comprising, in combination, a resonant cavity, paramagnetic material positioned within said cavity, means for subjecting said paramagnetic material to a magnetic field, a source of electromagnetic energy having a frequency which varies from one side of the frequency corresponding to the energy difference between two levels of electron spins in said paramagnetic material to the other side of said corresponding frequency, means for feeding said electromagnetic energy to said cavity, means for feeding other electromagnetic energy of signal frequency into said cavity and for conveying amplified electromagnetic energy of signal frequency from the cavity, and means for periodically changing the quality factor Q_c of said cavity to thereby change the total quality factor Q_t to a negative value to permit the buildup of oscillations of said signal frequency and thereafter restoring the cavity quality factor Q_c to substantially its original value to change the total quality factor Q_t to a positive value and quench said oscillations, the periodic buildup and quenching of oscillations in said cavity providing for superregenerative amplification.

3. In superregenerative apparatus for amplifying electromagnetic energy and employing stimulated emissions of radiation, in combination, a resonant cavity, paramagnetic material positioned within said cavity, means operatively connected to said cavity and paramagnetic material for providing state preparations of the material and providing a temporary negative Q for the material while the material has an excess population of electrons with high energy spin states, said cavity normally having a positive quality factor Q_c which is smaller numerically than the negative quality factor Q_m of the paramagnetic material whereby the total quality factor Q_t of the cavity and paramagnetic material is normally positive, and means for periodically increasing the quality factor Q_c of said cavity to thereby change the total quality factor Q_t of the cavity and material to a negative value which permits the buildup of oscillations in said cavity and thereafter decreasing the quality factor Q_c of said cavity to restore the total quality factor Q_t to a positive value and stop the buildup of said oscillations, the periodic buildup and quenching of said oscillations providing for superregenerative amplification.

4. Apparatus for superregeneratively amplifying electromagnetic energy comprising, in combination, a resonant cavity, paramagnetic material positioned within said cavity, means for feeding electromagnetic energy into said cavity and for conveying amplified electromagnetic energy from the cavity, means for subjecting said paramagnetic material to a magnetic field, ferrite material coupled to said cavity, means for subjecting the ferrite material to a variable magnetic field to vary the effective quality factor Q of the cavity, and means for feeding electromagnetic energy to said cavity to invert the populations of energy levels of electrons in said paramagnetic material.

5. Apparatus for superregeneratively amplifying electromagnetic energy comprising, in combination, a resonant cavity, paramagnetic material positioned within said cavity, means for feeding electromagnetic energy into said cavity and for conveying amplified electromagnetic energy from the cavity, means for subjecting said paramagnetic material to a magnetic field, further means for subjecting the paramagnetic material to a magnetic field which is in the same direction as the field produced by said first-mentioned subjecting means to vary the effective quality factor Q of said cavity, and means for feeding electromagnetic energy to said cavity to invert the population of the energy levels of electrons in said paramagnetic material.

6. In apparatus for superregeneratively amplifying electromagnetic energy, a resonant cavity, paramagnetic material positioned within said cavity, means for feeding electromagnetic energy into said cavity and for conveying amplified electromagnetic energy from the cavity, means operatively connected to said cavity to invert the population of the energy levels of electrons in said paramagnetic material, means for periodically driving the effective quality factor Q_t of said cavity together with the paramagnetic material contained therein negative, and means for forcing said paramagnetic material to a state approaching thermal equilibrium after populations of energy levels of electrons in the paramagnetic material are inverted and the said effective quality factor Q_t is made negative to thereby change the total effective quality factor Q_t to a positive value, the periodic change of the effective quality factor Q_t between negative and positive values providing for the periodic buildup and quenching of oscillations in said cavity, said periodic buildup and quenching of oscillations providing for superregenerative amplification.

7. In apparatus for superregeneratively amplifying electromagnetic energy, a resonant cavity, paramagnetic material positioned within said cavity, means for conveying electromagnetic energy to and from said cavity, means operatively connected to said cavity for first inverting the populations of energy levels of electrons in said paramagnetic material, means for thereafter driving the effective quality factor Q_t of said cavity and the paramagnetic material contained therein negative over a predetermined time interval, and means operable subsequent to the initiation of said predetermined time interval for forcing said paramagnetic material to a state of substantial thermal equilibrium, said last-named means including means for applying a 90 degree pulse of electromagnetic energy of predetermined frequency to said cavity and material.

8. Apparatus for superregeneratively amplifying electromagnetic energy comprising, in combination, a resonant cavity, paramagnetic material positioned within said cavity, means operatively connected to said cavity for conveying electromagnetic energy to and from said cavity, means for first inverting the populations of energy levels of electrons in said paramagnetic material by the application of a 180° pulse of electromagnetic energy, means including ferrite material for thereafter driving the effective quality factor Q_t of said cavity and the paramagnetic material contained therein negative over a predetermined time interval, and means operable subsequent to the initiation of said predetermined time interval for forcing said paramagnetic material to a state of substantial thermal equilibrium.

9. Apparatus for superregeneratively amplifying electromagnetic energy comprising, in combination, a resonant cavity, paramagnetic material positioned within said cavity, means for conveying electromagnetic energy to and from said cavity, means operatively connected to said cavity for first inverting the populations of the energy levels of elections in said paramagnetic material by adia-

batic rapid passage, means for thereafter driving the effective quality factor Q_t of said cavity and the paramagnetic material contained therein negative over a predetermined time interval, and means operable subsequent to the initiation of said predetermined time interval for forcing said paramagnetic material to a state of subsequential thermal equilibrium.

10. In apparatus for superregeneratively amplifying electromagnetic energy, the combination of stationary paramagnetic material positioned within a resonant cavity, means operatively connected to said cavity for inducing in said paramagnetic material a temporary excess of electron spins having high energy states and thereby providing a negative quality factor Q_m for said paramagnetic material, and means for periodically varying the effective total quality factor Q_t of said cavity and the paramagnetic material contained therein between positive and negative values, said last-named means including means for varying the value of the quality factor Q_c of the cavity alone between predetermined limits, the periodic varying of the total quality factor Q_t of the cavity and paramagnetic material providing for the periodic buildup and quenching of oscillations in said cavity.

11. In combination, means for detecting electromagnetic energy, gating means for intermittently rendering said detecting means operable, a resonant cavity, paramagnetic material positioned within said cavity, means for

conveying electromagnetic energy to said cavity and from said cavity to said detecting means, means operatively connected to said cavity for first inverting the populations of energy levels of electrons in said paramagnetic material, means for thereafter driving the effective quality factor Q_t of said cavity and the paramagnetic material contained therein negative over a predetermined time interval, and means to cause said gating means to render said detecting means operable subsequent to the initiation of said predetermined time interval and inoperable prior to termination of said predetermined time interval.

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