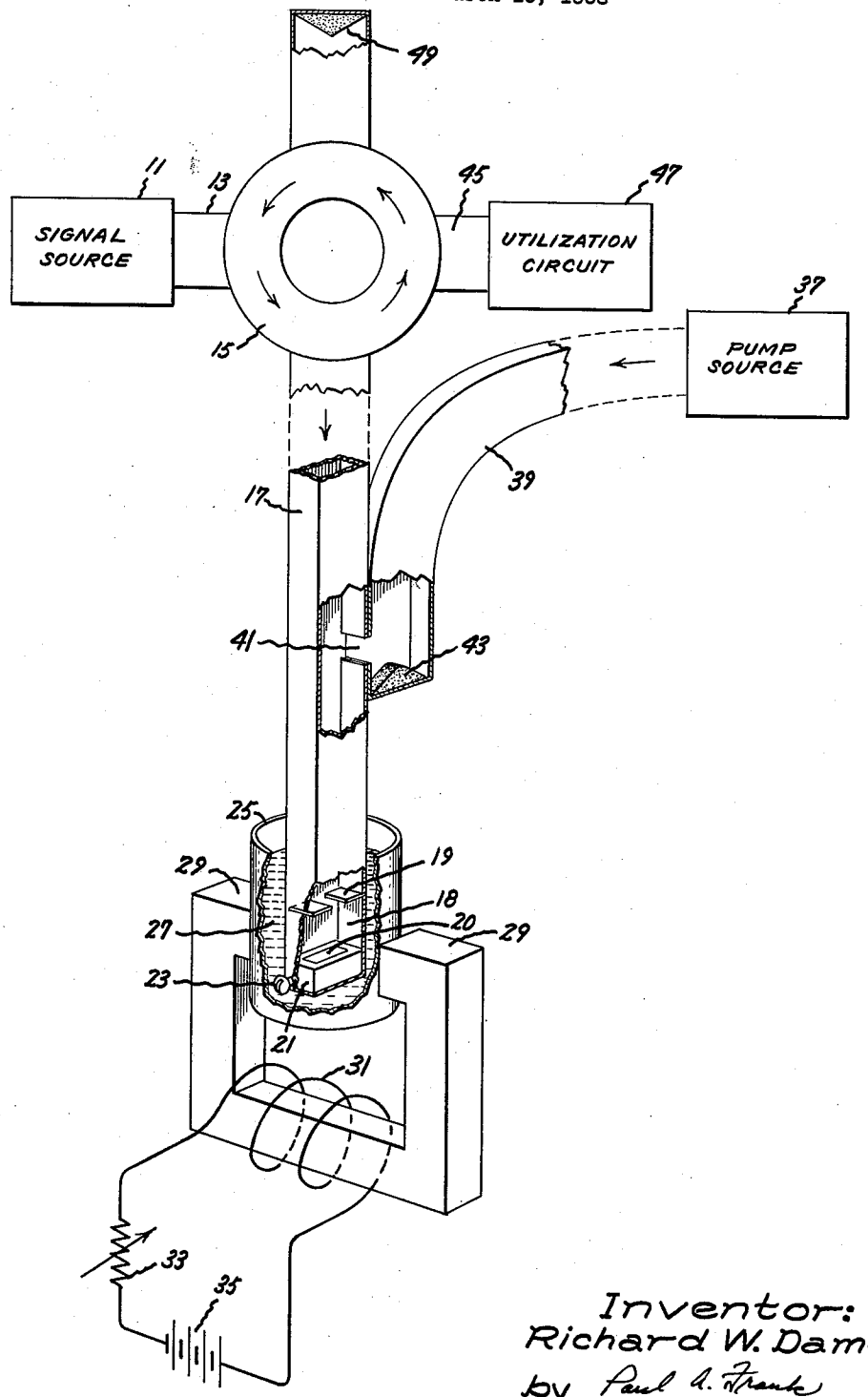
Nov. 13, 1962 R. W. DAMON 3,064,201

PRESSURE TUNED THREE-LEVEL PARAMAGNETIC MASER

Filed March 19, 1958



Inventor:
Richard W. Damon,
by Paul A. Frank
His Attorney.

United States Patent Office

3,064,201

Patented Nov. 13, 1962

3,064,201

PRESSURE TUNED THREE-LEVEL PARAMAGNETIC MASER

Richard W. Damon, Schenectady, N.Y., assignor to General Electric Company, a corporation of New York

Filed Mar. 19, 1958, Ser. No. 722,556

6 Claims. (Cl. 330—4)

The present invention relates to a three-level paramagnetic maser for amplifying microwave signals.

An amplifier has been recently developed in which the properties of paramagnetic materials are utilized. It is called a "maser," which is an acronym derived from the principle of operation: microwave amplification by stimulated emission of radiation. The operation is based upon electron spins, which produce an effect comparable to that obtained with a dipole magnet mounted on a gyroscope.

In the atoms of most materials the electron spins are "paired" such that for every electron spinning in one direction, another electron spins in the opposite direction. The magnetic dipole moments of each "pair" of electron spins cancel leaving no net magnetic effect. In certain solids, however, this pairing of electrons is incomplete and elements in the crystal, usually ions, which are fixed in location, can be found with unpaired electrons localized in them. When one of these ions—called paramagnetic ions—is placed in a magnetic field, it has an orientational energy of a magnitude depending upon the angle between the magnetic dipole of the unpaired spins and the applied field. When the dipoles are aligned with the field, the electrons have their lowest energy. They have highest energy when the dipoles oppose the applied field. The separation between these energy levels is a function of the applied magnetic field.

According to the quantum theory, an electron moving from a level of energy W_H to a lower energy level of W_L emits radiation of frequency $f=(W_H-W_L)/h$, wherein h is Planck's constant. The signal frequencies that a maser amplifies are approximately the same as the frequency associated with two energy levels of the maser paramagnetic material.

In three-level masers, the amplification process is related to three energy levels, two of which produce amplification while the third supplies energy to the system. The orientational energies of the spins must be capable of being changed directly from the lowest energy level of these three levels to the highest level without assuming the value of the intermediate level. Most maser materials do not have this property but must be specially operated to obtain it. In one three-level maser system, transitions from the lowest energy level to the highest are obtained directly through use of an applied direct magnetic field which interacts with the electric field created by the ions and atoms in the immediate vicinity of the paramagnetic ions.

If the ions and the atoms immediately surrounding each paramagnetic ion produce a symmetrical electric field, the shapes of the orbits of the electrons around the paramagnetic nuclei are not affected by the presence of these ions and atoms. But asymmetrical fields cause the orbits of the electrons around the paramagnetic nuclei to be extended in the shapes of ellipses. The electrons moving in these elliptical orbits produce a magnetic field affecting the dipole magnetic moment of the spinning electrons. If a direct magnetic field having a strength comparable to the magnetic field produced by this distortion of the electron orbits is applied so that it has a component at right angles to the axis of the electric field in the material, transitions from the lowest energy level to the highest energy level are possible to permit efficient amplification.

In these maser systems, signals having only a narrow range of frequencies can be amplified because if the external direct magnetic field is changed in order to alter the energy levels and thus the frequency that can be amplified, this field varies from the magnitude of the internal magnetic field produced by the orbit distortions. The result is an adverse effect upon the transitions of the electron spins between energy levels and consequently a decrease in amplification. Thus, before amplifying a signal of a certain frequency one must find a paramagnetic material having an internal field comparable to the applied magnetic field for this frequency. Obviously, it would be advantageous if the system were adjustable so that many frequencies could be amplified through the utilization of a single paramagnetic crystal.

Accordingly, an object of the present invention is to provide an improved three-level maser system.

Another object of the present invention is to provide a three-level maser system that can be adjusted to amplify signals over a range of frequencies.

A further object of the present invention is to provide a three-level maser system having a high gain over a greater range of frequencies than prior three-level maser systems.

These and other objects are achieved in one embodiment of my invention in which a crystal of paramagnetic material is subjected to an external pressure causing the internal crystal electric field to have different magnitudes at the paramagnetic ions along the three principal axes.

The novel features that I believe are characteristic of my invention are set forth in the appended claims. My invention itself, together with further objects and advantages thereof may best be understood by reference to the following description, taken in connection with the accompanying drawing, in which the single FIGURE illustrates a preferred maser amplifier embodiment of my invention.

In the figure those circuit elements which may in themselves be entirely conventional and whose details form no part of the present invention have been indicated in a simplified block form with appropriate legends. I have illustrated a signal source 11 of the signals to be amplified, which source may be, for example, a radar antenna receiving echo signals from an object in space. The signals from source 11 are guided by a wave guide 13, a circulator 15, and another wave guide 17 to a cavity resonator 18 formed by irises 19. In the bottom of cavity resonator 18 a crystal of maser material 20, which has at least two unpaired electrons per paramagnetic ion, is retained within some insulating material 21 such as polystyrene. Crystal 20 which preferably in an insulator so that microwaves will penetrate it deeply and which preferably has zero nuclear magnetic moment, can be formed from: gadolinium ethyl sulfate diluted with lanthanum ethyl sulfate, potassium chromicyanide diluted with potassium cobalticyanide, nickel silicofluoride diluted with zinc silicofluroide or some other suitable paramagnetic material. At a side of cavity resonator 18 a threaded screw 23 is positioned so that when turned it applies pressure on the insulating material 21 which then distorts the maser crystal 20.

Cavity resonator 18 is within a cryostat 25 containing a low temperature coolant 27, such as liquid helium, for cooling crystal 20 to a few degrees above absolute zero. A variable strength D.C. (direct current) magnet having poles 29 and winding 31 submerges maser crystal 20 in a direct magnetic field, the magnitude of which can be controlled by a variable resistor 33 that controls the amount of the current flowing through winding 31 from a source of direct voltage 35. By adjusting this field, a separation in energy levels can be obtained within the paramagnetic crystal 20 such that it amplifies the signal from source 11.

For amplification, crystal 20 must be energized by microwave energy at a frequency approximately equal to W_3-W_1/h, wherein W_3 and W_1 are the highest and lowest energy levels respectively, of the three energy levels utilized in the amplification process. Of course, the spacing of the energy levels, W_3-W_1, depends on the magnitude of the direct magnetic field. In effect, crystal 20 "pumps" energy from the frequency of this microwave energy to the frequency of the applied signal, thereby amplifying the applied signal. For this reason, the microwave energy is called the "pump energy" and its source the "pump source." In the figure the microwave energy, which is provided by a pump source 37, is guided by a wave guide 39 to a directional coupler comprising a hole 41 in wave guide 17 and some absorbing material 43. The microwave energy passes through hole 41 to wave guide 17 and thence to cavity resonator 18.

After amplification, the signal reflects out of cavity resonator 18 up wave guide 17 to circulator 15, then to wave guide 45 which guides the signal to a utilization circuit 47 that, for example, in a radar application may be an oscilloscope. A matched load 49 prevents energy from the utilization circuit 47 from reaching the signal source 11 from where some of it might be reflected into wave guide 17.

To understand the operation of my maser system the electrical fields in the maser material must again be considered. If the electrical fields at the paramagnetic ions are different in magnitude along the three principal directions, or in other words if the fields are asymmetrical, direct transitions from the lowest energy level to the highest energy level of the three energy levels are permitted. Preferably the asymmetry is such that the crystal field has a component of rhombic or lower symmetry. Most crystals do not have a significant crystal field of low symmetry in their natural form. However, I have discovered that such a field component can be induced by applying to the crystal an external pressure that distorts the unit cell of the crystal such that the desired transitions are permitted. This pressure not only permits the desired transitions but for those cells containing paramagnetic ions with four or more unpaired spins per ion, three energy levels are obtained between which transitions are permitted even in the absence of a magnetic field. Consequently, the D.C. magnet with poles 29 may be dispensed with. In such maser applications the energy level spacing, which determines the frequency that the crystal 19 amplifies, can be adjusted over a small range by pressure changes obtained by moving the screw 23.

If a direct magnetic field is used, the magnetic field produced by the distortion of the orbits of the electrons around the paramagnetic ion nuclei can be adjusted by changing the pressure on crystal 20 to a value suitable to the applied magnetic field. Consequently, the applied magnetic field can be adjusted to produce amplification of signals with many different frequencies. The correct crystal distortion can be maintained for wide variations in the magnitude of the applied magnetic field and thus maximum amplification obtained at many frequencies.

There are, of course, ways of applying pressure to the maser crystal 19 other than by using a screw 23. For example, a more permanent technique is the encapsulation of the paramagnetic salt by immersion in a liquid insulating material such as water, and also some glasses that subsequently expand upon solidifying, thereby exerting pressure on the crystal 20.

While the invention has been described with respect to certain specific embodiments, it will be appreciated that many modifications and changes may be made by those skilled in the art without departing from the spirit of the invention. I intend, therefore by the appended claims to cover all such modifications and changes as fall within the true spirit and scope of my invention.

What I claim is:

1. A three-level maser system comprising a source of signal that is to be amplified, a maser crystal including paramagnetic elements having at least two unpaired electron spins per element establishing at least first, second and third energy levels in ascending order according to number, said crystal exhibiting interior electric and magnetic fields, means for conducting said signal to said maser crystal at a first frequency corresponding to the difference between the second and third levels, means for applying a higher frequency pump signal to said crystal corresponding to the energy difference between said first and third levels, mechanical means for physically compressing said crystal to a selectable degree, the compressing action distorting the crystal structure and interior electric field of said crystal which alters the magnetic field interior to said crystal through altering the electron orbits of said paramagnetic elements, means for submerging said crystal in a direct magnetic field having a magnetic field strength of the same order of magnitude as the magnetic field interior to said crystal and having a component perpendicular to the internal electric field, and means for conducting the amplified output signal from said crystal for utilization purposes.

2. A three-level maser system comprising a source of signal that is to be amplified, a maser crystal including paramagnetic elements with at least four unpaired electrons per element, wherein each paramagnetic has at least three energy levels, W_3, W_2, and W_1, wherein W_2 is the intermediate energy level, mechanical means for physically compressing said maser crystal acting to alter internal crystal fields for permitting transitions between the lowest energy level W_1 to the highest energy level W_3, means for conducting the signal that is to be amplified to said maser crystal, means for conducting a microwave power signal to said crystal of a frequency approximately equal to W_3-W_1/h, wherein h is Planck's constant, and means for conducting the output of said maser crystal to a utilization circuit.

3. A three-level maser system comprising maser material containing paramagnetic elements having at least two unpaired electrons per element, said paramagnetic elements therefore exhibiting at least three energy levels, mechanical means for applying external physical pressure to said maser material for compressing the same causing the maser material surrounding each paramagnetic element to produce asymmetrical internal electric and magnetic fields at said element, means for applying an external magnetic field thereto of substantially equivalent strength to said internal magnetic field at an angle to the electric field whereby transitions from the lowest of said three energy levels to the highest energy levels of three levels are permitted, means for subjecting said maser material to an electromagnetic power signal at a frequency corresponding to the difference in energy levels of two of said three energy levels, and means for abstracting from said maser material electromagnetic energy having a frequency corresponding to a difference in energy levels of two or said three energy levels including the highest energy level of said two energy levels and an intermediate level.

4. The maser system as defined in claim 3 wherein said means for applying pressure is adjustable to produce different amounts of external pressure on said maser material whereby said maser system can be adjusted over a wide range of frequencies of operation.

5. In a three-level maser system, a crystal of paramagnetic material containing paramagnetic elements having at least two unpaired electrons per element and characterized by a plurality of energy levels, an array of atoms arranged about each paramagnetic element in a predetermined crystalline order, said crystal being responsive to physical pressure variation to alter the disposition of said atoms about each paramagnetic element from said predetermined crystalline order to change the internal crystal electric and magnetic field about a paramagnetic element, adjustable mechanical means for adjustably compressing

said crystal for causing atoms surrounding each paramagnetic element to thus alter their positions from said predetermined crystalline order, and electrical means for raising the energies of said paramagnetic elements with an applied radio frequency wave corresponding in frequency to the difference between a pair of said energy levels.

6. In a three-level maser system, a crystal of material containing paramagnetic elements having at least two unpaired electrons per element characterized by a plurality of energy levels, ions arranged about each paramagnetic element in a predetermined crystalline order, said crystal being responsive to an adjustable physical pressure to produce an assymmetrical disposition of said ions about each paramagnetic element different from said predetermined crystalline order to change the internal crystal electric and magnetic field about a paramagnetic element, adjustable mechanical means for adjustably compressing said crystal to produce said asymmetrical disposition of elements to thereby cause the internal electric field produced at the paramagnetic elements to have a component of symmetry at least as low as rhombic symmetry, and means for raising the energies of said paramagnetic elements with an applied radio frequency wave corresponding in frequency to the difference between a pair of said energy levels.

References Cited in the file of this patent

UNITED STATES PATENTS

2,240,293	Goddard	Apr. 29, 1941
2,762,871	Dicke	Sept. 11, 1956
2,782,280	Bickford	Feb. 19, 1957
2,825,765	Marie	Mar. 4, 1958
2,878,454	Leming et al.	Mar. 17, 1959
2,894,224	Iversen	July 7, 1959
2,976,492	Seidel	Mar. 21, 1961

OTHER REFERENCES

Bloemberger: Physical Review, vol. 104, No. 2, Oct. 15, 1956, pages 324–327.

Feher: Physical Review, vol. 105, No. 2, January 1957, pages 760–763.

Braunstein: Physical Review, vol. 107, No. 4, Aug. 15, 1957, pages 1195–1196.

"Introduction to Solid State Physics," Kittel, 1956 (John Wiley & Sons of New York), pages 229 and 230 relied on.