May 17, 1966 M. W. MULLER 3,252,111

PULSED FERROMAGNETIC MICROWAVE GENERATOR

Filed April 24, 1962

FIG. 1

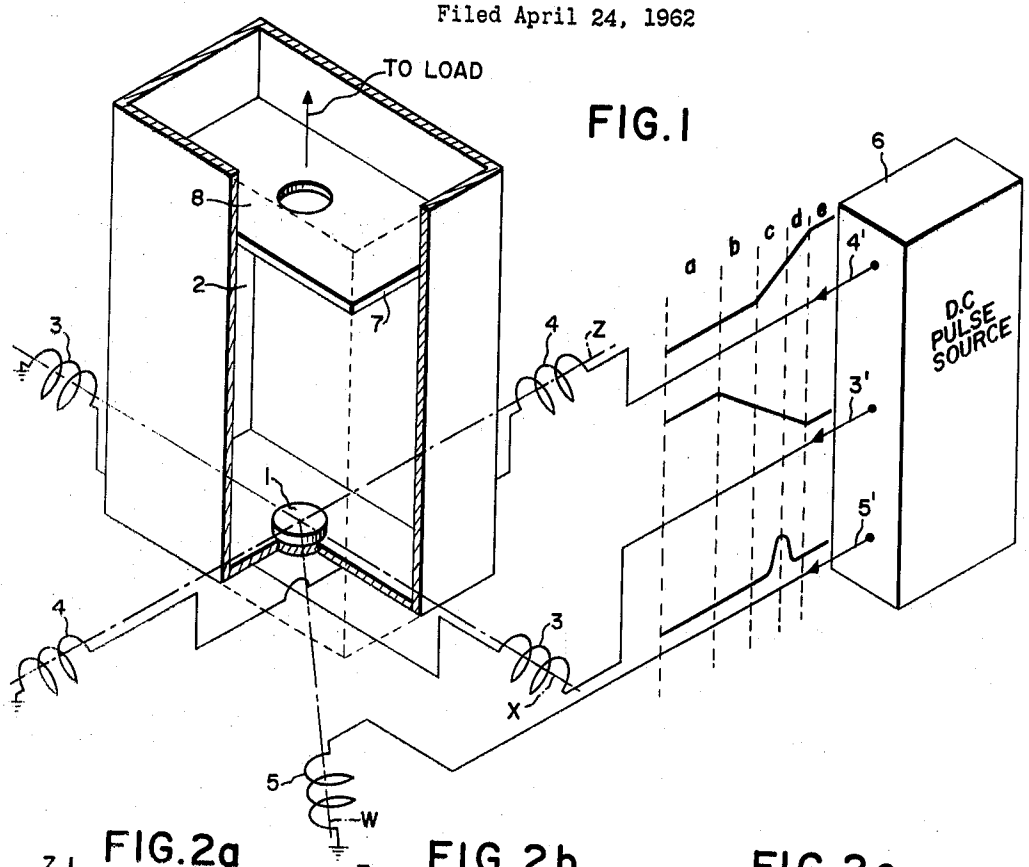


FIG. 2a

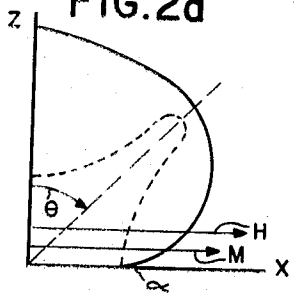


FIG. 2b

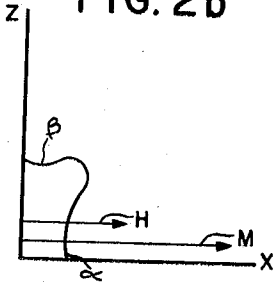


FIG. 2c

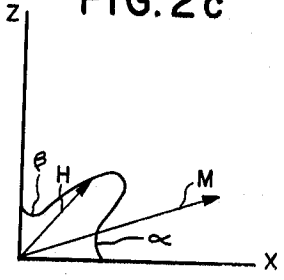


FIG. 2d

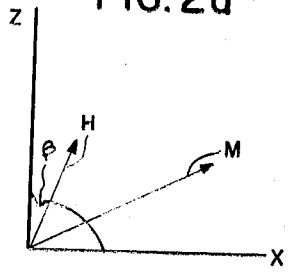
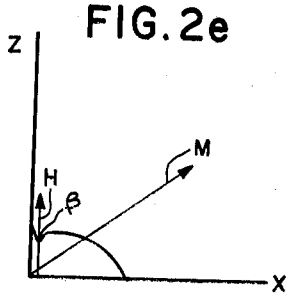


FIG. 2e



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United States Patent Office 3,252,111
Patented May 17, 1966

3,252,111

PULSED FERROMAGNETIC MICROWAVE GENERATOR

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Filed Apr. 24, 1962, Ser. No. 189,804
4 Claims. (Cl. 331—96)

The present invention relates to the generation of microwave frequency power, and more particularly to a novel microwave radiation technique which utilizes the interaction of a pulsed magnetic field with a ferromagnetic crystal exhibiting metastable magnetization.

It has been realized for several years that if the magnetization of a saturated ferromagnet can be brought into a state in which it is transiently unaligned with respect to an external static (D.C.) magnetic field, the magnetization can then precess about this field and radiate microwave pulse power at the precession frequency. Further, it has been realized that such a device would have certain potential advantages, including a high power output due to the large number of electron spin which contribute to the magnetization even at room temperature.

A summary of prior devices which have been utilized or proposed for this purpose is given in the following papers by B. J. Elliot et al.: "Pulsed Ferrimagnetic Microwave Generator," Journal of Applied Physics, vol. 31, pp. 400S–401S (May 1960); "Pulsed Millimeter-Wave Generation Using Ferrites," I.R.E. Trans., vol. MTT–9, pp. 92–94 (Jan. 1961). In general, the power generation schemes utilized in these prior devices require either impractically short rise times in the pulsing of the D.C. field, or the addition of a microwave power supply.

It is the principal object of the present invention to provide a novel pulsed ferromagnetic microwave generator which utilizes pulsed D.C. fields of practical rise times without requiring microwave excitation. Generally speaking, this is accomplished by putting a ferromagnetic sample into a state of metastable magnetization and then removing the metastable energy minimum of the sample whereby the magnetization precesses about the direction of absolute energy minimum.

Various features and advantages of the present invention will become apparent upon a perusal of the following specification taken in connection with the accompanying drawing wherein:

FIG. 1 is a schematic representation of a generator in accordance with the present invention, the microwave structure being shown in isometric view with the exterior walls broken to expose the interior details, and

FIGS. 2*a*, 2*b*, 2*c*, and 2*e* are polar energy diagrams for explaining the interaction of the sample magnetization and applied field during the various pulsing intervals *a* through *e* in the generator of FIG. 1.

The samples of interest in the present invention include those in which the uniform magnetization of a saturated monocrystalline ellipsoid can assume two or more orientations. The energy of the sample is lowest in one of these orientations; the others are metastable, corresponding to local but not absolute minima of the energy surface. Such a sample is said to exhibit metastable magnetization. As is well known, such samples may be obtained, for example, from several known compounds of both cubic and hexagonal structure with suitable crystalline anisotropy constants.

Referring to FIG. 1, we consider, for purposes of illustration, a thin disc **1** of cubic material with positive anisotropy cut parallel to a (100) plane and thus containing four directions (100) of easy magnetization. The sample is mounted on the end wall of a rectangular cavity resonator **2** with one of these easy directions oriented in the direction x perpendicular to the narrow walls of the resonator.

Disposed about the sample **1** and supplying magnetic fields thereto are coils **3**, **4** and **5**, indicated in an exploded and schematic manner. The coils **3** and **4** are disposed respectively along the mutually perpendicular x and z axes; and the coil **5** is disposed along axis w which makes an angle of 135° with the z axis. The D.C. pulse source **6** represents any well known circuit arrangement for supplying current pulses to the coils **3**, **4**, **5** which are of the general form indicated above the lines **3'**, **4'**, **5'** coupling the source **6** to the coils.

FIG. 2 illustrates the interaction of the sample **1** with the resultant field H established during the various pulsing intervals *a* through *e*.

During the interval *a*, a field is established in the x direction which is of sufficient magnitude to produce a saturation magnetization M of the sample. The dotted line is a polar plot of the free energy of the anisotropic sample crystal in the absence of an external field, this plot displaying energy minima along the x and z axes and an energy maximum at an angle θ (measured from the z axis) of 45°. Since the saturating field H is larger than the anisotropy field H_a of the crystal, the net energy plot of the sample, shown by a solid curve, exhibits a single energy minimum α which is in the direction (x) of the applied field.

During the interval *b*, the applied field H is reduced to a value in the range $\frac{1}{4}H_a<H<H_a$ whereby these fields interact to produce a net energy plot wherein a local energy minimum β, due to the anisotropy field, appears in the z direction.

During the interval *c*, an increasing field is applied in the z direction via coil set **4** (and the x direction field is preferably decreased) whereby the resultant applied field H rotates towards the z axis. When the angle θ of the H vector is less than 41°, the energy minimum β near the z axis becomes deeper than the energy minimum α near the x axis. However, the magnetization vector M is constrained to the less deep minimum α since there is an intervening energy maximum (potential barrier). This is a condition of metastable magnetization.

During interval *d*, the resultant field H, and its tendency to set up an energy minimum, continues to rotate toward the z axis until, at the onset of interval *e*, it is substantially in the z direction. The local minimum α disappears and the magnetization M is left in an unstable position at an angle to the applied field H.

During the interval *e*, the magnetization M undergoes precession about the new equilibrium z direction, thereby radiating a pulse of energy into the surrounding cavity resonator **2** at the precession frequency. The cavity resonator is tuned for resonance at the radiation frequency in a dominant $TE_{1,0n}$ mode, the sample **1** being located in a position of maximum magnetic field and minimum electric field for such a mode. The power so generated is coupled via iris plate **7** and connecting waveguide **8** to an external load, for example an antenna.

Taking dilute (approximately 20%) cobalt ferrite as an example, the instability of interval *e* sets in when θ is reduced to 34.3° for $H=\frac{1}{2}H_a$. To minimize the effect of the radiationless growth of spinwaves which precedes this instability, it is desirable to traverse the spinwave instability region in a time short compared to the instability growth time. To this end a separate pulsing coil **5** set at right angles to the instability direction of approximately $\theta=45°$ may be used.

For sufficiently thin samples

$$\left(\text{ratio}\ \frac{\begin{matrix}N_T=\text{transverse}\\ \text{demagnetization factor}\end{matrix}}{\begin{matrix}N_L=\text{longitudinal}\\ \text{demagnetization factor}\end{matrix}}\ \text{less than about .01}\right)$$

a pulse having a rise time on the order of 20 nanoseconds is sufficient, which is a much less stringent condition than that presented by prior D.C. pulse schemes. In particular, it is to be noted that the effective precession frequency just prior to pulsing approaches zero, so that one is not troubled with the requirement that the field is to be pulsed in a time short compared to a precession cycle. As a further advantage, it should be noted that the magnetization may be initially placed at a substantial angle with reference to the field about which it preceses, 48.7° in the present example, whereas prior schemes using microwave excitation are limited to angles on the order of 1° with a corresponding limitation on the pulse power generated.

The exact frequency radiated depends in general on the values of H, the first and second order anisotropy constants K_1 and K_2, and the magnetization M. For a (100) disc with $N_T=0.1$ and $N_L=0.8$ cut from a material with $4\pi M=5000$ gauss, first order anisotropy field $H_a=2000$ oersteds, and an electron spin g-factor of 2.3, the radiated frequency varies from 8 to 12 kmc./sec. as the applied field H is changed from 1700 to 1100 oersteds. The energy that is potentially available for the radiation is the difference between the metastable and final energy minima which, for this example, varies from 5×10^4 to 10^4 ergs per cm.^{3} over this frequency range. For a 0.01 cm.^{3} sample, a 1 μsec. pulse, and an efficiency of 10%, this would furnish a pulse power of 1 to 5 watts.

The cobalt ferrite example is characterized by a rather large ferromagnetic resonance linewidth and hence a correspondingly short free precession time during which pulse power may be obtained. For longer pulses a material such as yttrium iron garnet, which exhibits an anomalous anisotropy at liquid helium temperatures, may be found useful.

Since many changes could be made in the above construction and many apparently widely different embodiments of this invention could be made without departing from the scope thereof, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

What is claimed is:

1. A device for generating high frequency power comprising: an anisotropic feromagnetic disk-like sample capable of exhibiting metastable magnetization; a cavity resonator having an end wall, said sample being mounted on such wall within said resonator at a location of maximum magnetic field for the resonant mode of said resonator at the precession frequency of said sample; first, second and third coil means respectively coupled to said sample, and disposed radially thereto, said first and second coil means being substantially perpendicular to each other; and pulsing current means coupled to said first coil and adapted for first magnetizing said sample for generating a magnetic field along a first axis defined by said first coil means, and for then reducing the current to said first coil to decrease the magnitude of such field, said pulsing current means coupled to said second coil means and adapted for increasing the current thereto so that such field rotates toward an axis intermediate the axes defined by said first and second coil means and for establishing a condition of metastable magnetization; said pulsing current means coupled to said third coil means for applying a pulse thereto so that such field rotates towards the axis defined by said second coil means to develop a condition of unstable magnetization, whereby pulsed energy is radiated in said cavity resonator.

2. A device according to claim **1** wherein said sample is a single crystal in the form of a disc sufficiently thin that the ratio of the transverse demagnetizing factor to the longitudinal demagnetizing factor is less than .01.

3. A solid-state microwave oscillator comprising: an anisotropic ferromagnetic material, a cavity resonator having an end wall, said material being mounted on such wall within said resonator at a location of maximum magnetic field for the resonant mode of said resonator at the precession frequency of said material, said material having anisotropic magnetization properties with energy minima in two different crystal directions, one of said minima being lower than the other, first coil means for establishing a magnetic field along a first axis defined by said first coil means; second coil means for rotating said magnetic field away from such first axis and towards a direction intermediate the first axis and a second axis defined by said second coil means, said first and second axes being substantially orthogonal, and third coil means for applying a magnetic field pulse substantially at right angles to such intermediate direction so that a condition of unstable magnetization is produced.

4. Apparatus for generating high frequency power comprising: a crystalline anisotropic material having directions of easy magnetization in at least first and second directions; a cavity resonator having an end wall, said material being mounted on such wall within said resonator at a location of maximum magnetic field that is established by tuning said resonator to a resonant mode at the frequency of precession of said material; and means for pulsing said material, including first, second and third coil means, said first and second coil means disposed orthogonally, said first coil means serving to establish a magnetic field, said second coil means serving to establish a condition of metastable magnetization, said third coil means serving to rotate the magnetic field by pulsing so that a condition of unstable magnetization arises, whereby pulsed energy is radiated in said cavity resonator.

References Cited by the Examiner

UNITED STATES PATENTS

2,873,370	2/1959	Pound	331—107
3,087,122	4/1963	Rowen	331—94
3,164,768	1/1965	Stiglitz et al.	330—4.8 X
3,165,711	1/1965	Drumheller et al.	333—1.1

ROY LAKE, *Primary Examiner.*