Some Techniques of Microwave Generation and Amplification Using Electron Spin States in Solids*

D. I. BOLEF† AND P. F. CHESTER†

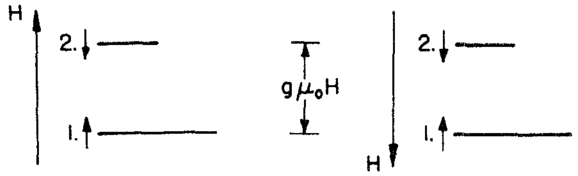
Summary—**Possible modes of operation of two-level solid state masers utilizing the techniques of population inversion used in nuclear magnetic resonance are described. Methods of continuous operation of two-level masers and their usefulness as microwave generators are discussed.**

INTRODUCTION

RECENTLY, several papers[1-7] have made clear the advantages to be expected of solid-state maser amplifiers with respect to noise figure, when compared with conventional microwave amplifiers, and with respect to tunability, bandwidth, power output, and simplicity, when compared with beam-type or gas cell masers.

The paper by Scovil[8] has described the first successful solid-state master oscillator, based on a three-level scheme and, therefore, inherently continuous in operation. The conditions under which such a scheme can be used, however, are somewhat circumscribed by the limited number of suitable paramagnetic materials and by considerations of "forbidden" transitions, relaxation times, and local oscillator power. Extension to operating temperatures appreciably above 1.2°K or to frequencies higher than X band is likely to depend on further investigation of paramagnetic materials. An upper frequency limit will eventually be set by the nonavailability of a source of saturating power. The inherent frequency-reducing characteristic of three-level masers precludes consideration of them as microwave generators.

Two-level solid-state masers, although basically intermittent in operation, should be realizable in practice with fewer restrictions on materials, operating temperature, frequency, and local oscillator power. The first attempted solid-state maser[1] was in fact based on a two-level scheme. It is the purpose of this paper to examine possible modes of operation and characteristics of two-level maser amplifiers, to suggest ways in which intermittency might be avoided, and to discuss the possibilities of two-level maser generators.



(a) (b)

Fig 1—(a) Energy levels of a free electron in a magnetic field. The population of a level is indicated schematically by the length of the horizontal line. (b) Situation after nonadiabetic field reversal.

INVERSION IN TWO-LEVEL SYSTEMS

Consider the two energy states for a free electron in a magnetic field H corresponding to magnetic moment parallel and antiparallel to the field, as shown in Fig. 1(a). The difference in energy is given by

$$E_2 - E_1 = h\nu = g\mu_0 H \tag{1}$$

where h is Planck's constant, ν the resonant frequency, μ_0 the Bohr magneton, and g has the value 2.0023 for a free electron. For a paramagnetic crystal in which the ions have an effective spin of $\frac{1}{2}$ and show no hyperfine interactions, it is a good approximation to use (1) with a suitably modified value of g. If the crystalline electric field is noncubic, g will be a function of the angle between the symmetry axis and the external magnetic field.

In a magnetic field the populations of the upper and lower states, N_2 and N_1 respectively, will in general not be equal and a spin magnetization M therefore will exist whose component along the field is given by

$$M_H = g\mu_0(N_2 - N_1)/2.$$

When the spin system is in equilibrium with the lattice at absolute temperature T,

$$\left[\frac{N_1}{N_2}\right]_{\text{equil}} = \exp.\, h\nu/kT$$

where k is Boltzmann's constant. This corresponds to an equilibrium magnetization M_0. Under nonequilibrium conditions, M_H relaxes to the value M_0 with a time constant T_1, the spin-lattice relaxation time.

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† Westinghouse Res. Labs., Pittsburgh 35, Pa.

[1] J. Combrisson, A. Honig, and C. H. Townes, "Utilisation de la resonance de spins électroniques pour réaliser un oscillateur ou un amplificateur en hyperfrequences," *Compt. Rend.*, vol. 242, pp. 2451–2453; May 14, 1956.

[2] N. Bloembergen, "Proposal for a new type solid state maser," *Phys. Rev.*, vol. 104, pp. 324–327; October 15, 1956.

[3] M. W. P. Strandberg, "Quantum mechanical amplifiers," PROC. IRE, vol. 45, pp. 92–93; January, 1957.

[4] J. P. Wittke, "Molecular amplification and generation of microwaves," PROC. IRE, vol. 45, pp. 291–316; March, 1957.

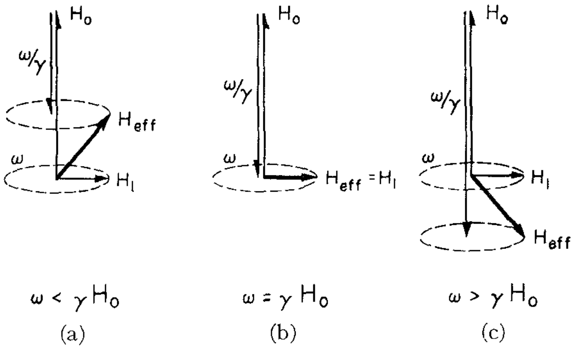
[5] M. W. Muller, "Noise in a molecular amplifier," *Phys. Rev.*, vol. 106, pp. 8–12; April 1, 1957.

[6] R. V. Pound, "Spontaneous emission and the noise figure of maser amplifiers," *Ann. Phys.*, vol. 1, pp. 24–33; April, 1957.

[7] K. Shimoda, H. Takahasi, and C. H. Townes, "Fluctuations in amplification of quanta," *J. Phys. Soc. Japan*, vol. 12, pp. 686–700; June, 1957.

[8] H. E. D. Scovil, "The three-level solid-state maser," this issue, p. 29.

Before maser action can be obtained, it is necessary for N_2 to be made greater than N_1, *i.e.*, for M_H to be made negative. When only two states exist this situation may be brought about in principle by exchanging populations between the states using one of the techniques familiar in transient nuclear resonance experiments.[9-12]



(a) (b) (c)

Fig. 2—The effective field in a frame of reference rotating about H_0 at frequency ω with the microwave field H_1, (a) ω below resonance, (b) at resonance, (c) ω above resonance.

An understanding of the two most common inversion techniques may be had by reference to the vector representation of Fig. 2. The paramagnetic sample is assumed to be in a steady magnetic field H_0 and subjected to a microwave field circularly polarized about the direction H_0, of amplitude H_1 and angular frequency ω. It will further be assumed that before the microwave field was switched on, the spin system was characterized by a magnetization M parallel to H_0. It is convenient to refer the subsequent motion of M to a coordinate system rotating about the H_0 axis with angular frequency ω. The effective field experienced in the rotating system is given by[13]

$$\overrightarrow{H}_{\text{eff}} = (\overrightarrow{H}_0 - \overrightarrow{\omega/\gamma}) + \overrightarrow{H}_1$$

where γ is the electron gyromagnetic ratio. Viewed in the rotating system, M will precess about H_{eff} with angular frequency Ω where

$$\Omega = \gamma H_{\text{eff}}.$$

Adiabatic Rapid Passage (ARP)

For a microwave field of frequency ω well below the value $\omega_0(=\gamma H_0)$ required for resonance, the appropriate field relationship is shown schematically in Fig. 2(a). If $(H_0-\omega/\gamma) \gg H_1$, H_{eff} is almost parallel to H_0. As ω is increased, H_{eff} diminishes in magnitude and inclination until at $\omega=\omega_0$ it becomes identical with H_1, Fig. 2(b). As ω is further increased well beyond ω_0, H_{eff} increases in magnitude and approaches an orientation antiparallel to H_0, Fig. 2(c).

If the change in H_{eff} is small during a precessional period of M, *i.e.*, in a time Ω^{-1}, M follows the changes in H_{eff} adiabatically. The orientation of M with respect to H_0 is, therefore, reversed as a result of the passage through resonance, *i.e.*, finally $N_2 > N_1$. The adiabatic condition may be written

$$(\gamma H_1)^{-1} \ll t$$

where t is the time to pass through the resonance half-width $\Delta\omega_0(=\gamma\Delta H_0)$. Passage through resonance by sweeping H_0 is entirely equivalent to sweeping ω. In both cases, inversion of the initial magnetization results, whichever the direction of the sweep.

Another condition originally thought necessary[14] for ARP was that t be much shorter than both the spin-lattice relaxation time, T_1, and the spin-spin relaxation time, T_2. More recent work[15] indicates that the condition on t is in fact less stringent and that provided H_1 is well above the value required for saturation, it is sufficient merely for $t \ll T_1$. It follows that materials with narrow lines or long T_1s will be most amenable to ARP. Experiments[16-18] has shown inversion by ARP to be particularly easy in certain inhomogeneously broadened lines[19] where the unresolved sublines are exceedingly narrow. Such lines may not be the most suitable for maser action, however, unless all the sublines are able to give up energy to the microwave signal field. Such a situation might be assured by radio frequency mixing among the sublines when these are due to hyperfine interactions. No experimental report of inversion by ARP in dipolar-broadened or exchange-narrowed lines has yet appeared, but a number of such lines with widths less than one oersted are known[20-22] and ARP should be possible in some of these with reasonable microwave driving

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[9] F. Bloch, W. W. Hansen, and M. Packard, "Nuclear induction experiment," *Phys. Rev.*, vol. 70, pp. 474–485; October 1, 1946.

[10] H. C. Torrey, "Transient notations in nuclear magnetic resonance," *Phys. Rev.*, vol. 76, pp. 1059–1067; October 15, 1949.

[11] E. L. Hahn, "Spin echoes," *Phys. Rev.*, vol. 80, pp. 580–594; November 15, 1950.

[12] E. M. Purcell and R. V. Pound, "A nuclear spin system at negative temperature," *Phys. Rev.*, vol. 81, pp. 279–280; January 15, 1951.

[13] I. Rabi, N. F. Ramsey, and J. Schwinger, "Use of rotating coordinates in magnetic resonance problems," *Rev. Mod. Phys.*, vol. 26, pp. 167–171; April, 1954.

[14] F. Bloch, "Nuclear induction," *Phys. Rev.*, Vol. 70, pp. 460–474; October 1, 1946.

[15] A. G. Redfield, "Nuclear magnetic resonance saturation and rotary saturation in solids," *Phys. Rev.*, vol. 98, pp. 1787–1809; June 15, 1955.

[16] A. M. Portis, "Rapid passage effects in electron spin resonance," *Phys. Rev.*, vol. 100, pp. 1219–1221; November 15, 1955.

[17] A. Honig, "Polarization of arsenic nuclei in a silicon semiconductor," *Phys. Rev.*, vol. 96, pp. 234–235; October 1, 1954.

A. Honig and J. Combrisson, "Paramagnetic resonance in As-doped silicon," *Phys. Rev.*, vol. 102, pp. 917–918; May 1, 1956.

[18] G. Feher and E. A. Gere, "Polarization of phosphorus nuclei in silicon," *Phys. Rev.*, vol. 103, pp. 501–503; July 15, 1956.

[19] An "inhomogeneously broadened" line is one in which the observed line width is an envelope of a number of narrower "sublines" due to a distribution of local magnetic fields at the paramagnetic centers. This distribution may arise from inhomogeneities in the applied magnetic field or from the presence of nuclear magnetic moments. By contrast a "homogeneously broadened" line is one in which the line width is due either to dipole-dipole interactions or to exchange interaction between the paramagnetic centers.

[20] R. A. Weeks, "Paramagnetic resonance of lattice defects in irradiated quartz," *J. Appl. Phys.*, vol. 27, pp. 1376–1381; November, 1956.

[21] B. Smaller, G. R. Hennig, and E. L. Yasaitis, "Paramagnetic resonance absorption in graphite compounds," *Phys. Rev.*, vol. 97, p. 239; January 1, 1955.

[22] J. E. Wertz and P. Auzins, "Crystal vacancy evidence from ESR," *Phys. Rev.*, vol. 106, p. 484; May 1, 1957.

power. Liquid helium temperatures are not expected to be necessary for successful ARP in some of the known materials.

180° Pulse

If the spin system in a magnetic field is subjected to a circularly polarized microwave field at the resonant frequency ω_0, the effective field is as shown in Fig. 2(b). The magnetization M, initially parallel to H_0, starts to precess about H_1 with angular velocity $\Omega = \gamma H_1$. Thus, after time t_π where

$$t_\pi = \frac{\pi}{\gamma H_1}, \tag{2}$$

M will be aligned antiparallel to H_0. If the microwave field is cut off at time t_π, the magnetization will be negative, *i.e.*, N_2 will be greater than N_1. Eq. (2) thus defines a "180° pulse." If H_1 does not exceed a few times ΔH_0 or if the microwave frequency deviates from resonance by as much as $(\Delta\omega_0)/2\pi$, or if (2) is not satisfied experimentally, the inversion will not be perfect. When a good 180° pulse can be produced, however, this technique has the advantage over ARP of requiring less time to accomplish and less average power from the microwave driving field. Pulse lengths between 10^{-8} and 10^{-6} seconds and amplitudes between 0.2 and 20 oersteds will be required for likely materials.

Nonadiabatic Field Reversal

Although this technique was used to invert Li^7 nuclear spin states in the classic negative temperature experiment of Purcell and Pound,[12] little or no attention has been paid to it in connection with solid-state masers. Consider the populations of the two energy levels for an electron in a magnetic field H as shown in Fig. 1(a). If the magnetic field is reversed in a time very much shorter than $(\gamma H)^{-1}$, the system suffers a sudden or nonadiabatic perturbation[23] with the result that the field is established in the reverse direction before the wave functions of the states have changed appreciably. The final situation, as shown in Fig. 1(b), is therefore that the more heavily populated state has become the state of higher energy and vice versa, the extra energy having been absorbed from the source of the changing magnetic field. Since the nonadiabatic condition is

$$\frac{dH}{dt} \gg \gamma H^2, \tag{3}$$

it will clearly be advantageous to reverse the smallest possible field, $H_{\min}$. The lower limit to $H_{\min}$ is set by the line width ΔH_0, or by field components normal to H_0. It should be sufficient to reduce the value of H adiabatically to a value several times larger than ΔH_0, reverse it nonadiabatically, and then increase it adiabatically to $-H_0$, all this taking place in a time much shorter than T_1. For a line of width 0.1 oersted, $H_{\min}$ might be 0.5 oersted and the reversal time for $H_{\min} \sim 5\times10^{-8}$ seconds. Such a rate of change of field is possible with pulse techniques or with a combination of high static field gradients and high translational velocities. The conditions should be easier for inhomogeneously broadened lines having sublines narrower than 0.1 oersted provided that the "spin diffusion time"[24] between sublines at low fields is much longer than the field reversal time for a given subline.

This technique has the one advantage of requiring no microwave driving field. It may, therefore, find application in the generation of short microwaves.

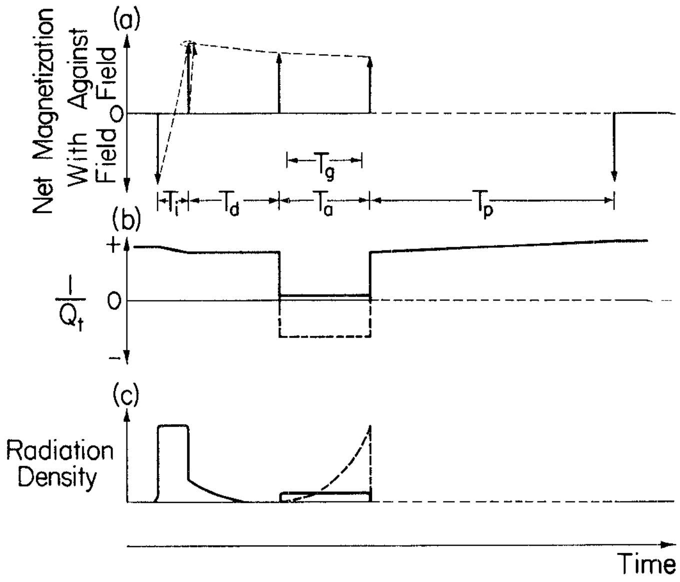

Fig. 3—Time sequence in a simple two-level maser (not to scale). (a) Magnetization vs time, (b) $(Q_t)^{-1}$ vs time, (c) radiation density in cavity vs time. In (b) and (c) the solid line refers to regenerative operation and the broken line to super-regenerative operation.

INTERMITTENT TWO-LEVEL MASERS

The interaction between the microwave signal which is to be amplified and the inverted spin system may be contrived with either a traveling-wave or a standing-wave (resonant cavity) structure. We shall consider only cavity-based structures.

It is apparent from the discussion of the previous section that, in a simple two-level maser, population inversion and amplification cannot proceed simultaneously and that some form of sequential operation is called for. The time cycle that is likely to be followed in such a maser may be divided into four main periods. Fig. 3 shows the behavior of spin magnetization, total Q, Q_t, and radiation density in the cavity during these periods. Inversion is effected during T_i by ARP or by a 180° pulse. The value of negative magnetization necessary for amplification is such as to make the magnetic Q, Q_m, close to (or smaller than) Q_a, the loaded Q of the cavity during

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[23] D. Bohm, "Quantum Theory," Prentice-Hall, Inc., New York, N. Y., ch. 20; 1955.

[24] A. M. Portis, "Spectral diffusion in magnetic resonance," *Phys. Rev.*, vol. 104, pp. 584–588; November 1, 1956.

amplification. Q_m is given by the expression

$$Q_m = V_s/(4\pi M_H \gamma T_2 \eta)$$

where V_s is the volume of the sample, and η the filling factor. Q_m is, of course, negative after inversion.

Radiation damping of the transverse moment induced by the driving field H_1 gives rise to an opposing radiation field H_R whose magnitude is given by

$$H_R = 4\pi\eta Q M_T,$$

where M_T is the component of M transverse to H_0.[25] In order to achieve inversion, H_1 must exceed H_R.[4] This condition can always be satisfied by making H_1 large enough. Unless the inversion process is accomplished perfectly, afterwards there remains a finite transverse moment and the radiation damping field associated with it. The resulting radiative loss from the spin system is negligible when the loaded cavity Q is much less than $-Q_m$ but becomes catastrophic when the loaded cavity Q is equal to or greater than $-Q_m$. One method of avoiding such losses is to vary the cavity Q with time so that for the inversion period T_i and for a short period T_d after it the loaded cavity Q is kept at some low value $Q_i < -Q_m$. The required variation of Q may be realized either by periodically coupling a load to the cavity or by altering H_0 to take the inversion frequency away from the cavity resonant frequency. During T_d, H_R decreases exponentially because of the transverse relaxation of M_T. For $T_d \gg T_2$, H_R will fall to a value less than that of the signal to be amplified and thereupon the spin system can be used for amplification. The sum of the times T_i and T_d must of course be much shorter than T_1.

For regenerative amplification, the loaded Q of the cavity is restored at the start of T_a to a value Q_a, such that $-Q_m \geq Q_a$, *i.e.*, Q_t becomes large but remains positive in sign. T_a must, of course, be much shorter than T_1 for constancy of gain ($T_a \sim 10^{-3} T_1$ for a 10 per cent fall-off in gain at 30 db). For super regenerative amplification[26] the loaded Q is restored to a value such that $-Q_m < Q_a$, *i.e.*, Q_t becomes negative. Oscillation builds up with an amplitude proportional to the signal present at the start of T_a and the gain is determined by τ, the time constant for build-up and by the duration of T_a. The amplifying period may be terminated by reducing the loaded cavity Q to the value Q_i. In a super-regenerator, a self-quenching action due to spin-lattice relaxation is possible if T_a is made of the order T_1.

During T_p, the electrons are brought back to the same normal (though not necessarily equilibrium) distribution as they had prior to inversion. The simplest method of achieving this is to allow time for spin-lattice relaxation to act, but as this requires a time of the order of T_1, it normally results in $T_a \ll T_p$, *i.e.*, in a poor duty factor. There are various methods of shortening T_p which may depend on the particular paramagnetic material used. In semiconductors, radiative excitation into the conduction band followed by recombination,[4,27] is a convenient method if it does not cause excessive sample heating. Another method is to dope the working material with a paramagnetic ion having a very short T_1[28] and having a transition which can be made degenerate with that of the working substance by a suitable change in field. When the signal is small enough or when gain variations from cycle to cycle are not objectionable, a simple way to prepare a normal distribution is a second inversion at the start of T_p.

The transfer characteristic of a two level regenerative maser will approach that of a continuous amplifier as the duty factor is made to approach unity, *i.e.*, as the inactive time $(T_i + T_d + T_p)$ is made much shorter than the active time T_a. This can only be brought about by "artificial" shortening of T_p. Since with presently known materials the minimum inactive time is likely to be of the order of microseconds, a high duty factor may involve values of T_a up to 10^{-4} seconds. For a gain fall-off of less than 10 per cent due to spin lattice relaxation over the active period a T_1 of the order 0.1 second, would then be required. While there is no difficulty in obtaining such long relaxation times in doped silicon below 4°K, when T_a is long the power output from the amplifier before saturation is low ($+10^{-9}$ watts in the above case). The linear power output may be increased at the expense of the duty factor by decreasing T_a. In certain applications, *e.g.*, in radio astronomy and microwave radiometry where the "signal" is just low-level noise power, a poor duty factor is quite acceptable. However, in such cases super-regenerative operation is to be preferred because of its greater linear power output and greater stability at high gains.[26]

The combination of the time cycling described above with intense transient magnetic fields should make possible the generation of submillimeter waves at a relatively high level of power, particularly if materials with high g values can be used. Such a technique, although intermittent, might well find application in fundamental research.

CONTINUOUS TWO-LEVEL MASERS

If continuous operation is desired in a two-level maser, there must be some mechanical transport of material from one situation in which it is inverted to another situation in which it is used.

An obvious method of achieving continuous population inversion and transport of material is depicted in Fig. 4. The paramagnetic material is mounted on the periphery of a rotating disk so as to pass in sequence

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[25] N. Bloembergen and R. V. Pound, "Radiation damping in magnetic resonance experiments," *Phys. Rev.*, vol. 95, pp. 8–12; July 1, 1954.

[26] P. F. Chester and D. I. Bolef, "Super-regenerative masers," PROC. IRE, vol. 45, pp. 1287–1289; September, 1957.

[27] G. Feher and R. C. Fletcher, "Relaxation effects in donor spin resonance experiments in silicon," *Bull. Amer. Phys. Soc.*, vol. 1, p. 125; March 15, 1956. (Pittsburgh Meeting.)

[28] G. Feher and H. E. D. Scovil, "Electron spin relaxation times in gadolinium ethyl sulphate," *Phys. Rev.*, vol. 105, pp. 760–762; January 15, 1957.

through a region of high field (b) which produces a positive magnetization, then into a cavity (c) excited by a suitable local oscillator and situated in a magnetic field gradient of form such that material in passing through the cavity (c) experiences ARP. The emerging material, now characterized by a negative magnetization, passes into a second cavity (d), situated in a uniform magnetic field, where amplification takes place at a frequency which may be considerably higher than the ARP frequency. The transit time from (c) to (d) must be much less than T_1 but long enough for the decay of any transverse magnetic moment. The transit time from (d) round to (c) must be long enough for the establishment of a positive magnetization. Thus, the rotational rates required depend on T_1 and on the conditions for ARP, and are entirely feasible for materials with T_1 greater than a few milliseconds. A field gradient over the first cavity of at least several times the line width is required for ARP.

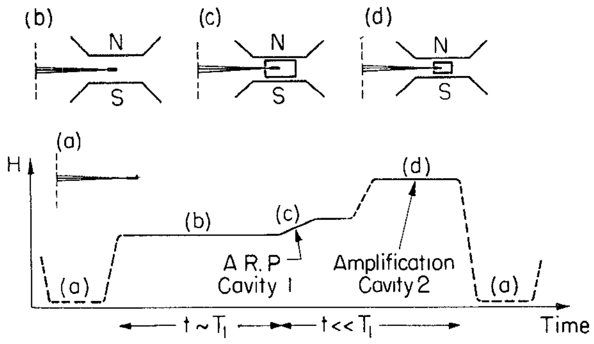

Fig. 4—Schematic representation of a continuous two-level maser using a rotating disk to achieve adiabatic rapid passage and transport of material. The magnetic field experienced by an electron is shown as a function of time. Also shown is the mechanical situation at four representative times.

A mechanically simpler device is conceivable if use can be made of a paramagnetic crystal in which the resonant frequency in fixed magnetic field is a strong function of the angle, Θ, which the crystalline field makes with the magnetic field. Such a material, situated in a cavity in a steady magnetic field, may be taken through resonance by altering Θ. Thus, ARP by crystal spinning is possible. The variation of the energy levels with Θ is in general somewhat complicated,[29] but takes on a particularly simple form for a paramagnetic ion of effective spin $\frac{1}{2}$ and no hyperfine structure. In this case, (1) holds with $g=(g_\parallel^2 \cos^2 \Theta + g_\perp^2 \sin^2 \Theta)^{1/2}$. Such a variation of g with Θ is shown in Fig. 5. If such a single crystal is situated in a doubly resonant cavity excited at its lower resonant frequency ν_1 by a local oscillator and is suitably rotated, it will undergo ARP at orientations marked (a) and (c) in Fig. 5.[30] If the spin system has a positive magnetization prior to passage through (a) and if the time taken to rotate from (a) to (b) is much shorter than T_1, amplification at the higher cavity frequency ν_2 is possible. A positive magnetization is reestablished after passage through (c). If ν_1 is made sufficiently close to ν_2 so that the time (a) to (c) is much shorter than the time (c) to (a), the cycle may be repeated indefinitely.

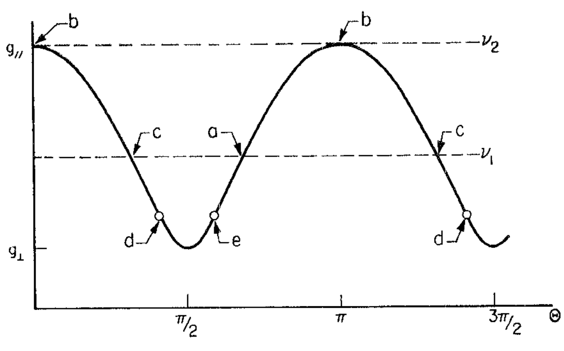

Fig. 5—The variation of g with angle between crystalline field axis and an external magnetic field for a simple case of anisotropy, $g=[g_\parallel^2 \cos^2 \Theta + g_\perp^2 \sin^2 \Theta]^{1/2}$.

If the specimen is made up of a number of crystallites oriented in the plane normal to the axis of rotation, there will always be some crystallites at the proper angle for amplification, which then proceeds continuously.

Possible materials (*e.g.*, sodium plutonyl acetate) for this maser do show hyperfine structure, however, which results in a mixing of energy levels near $\Theta=\pi/2$ and $3\pi/2$, and the magnetization is not expected to survive passage through these angles. The problem may be avoided if a positive magnetization can be achieved prior to (a) at some angle (*e*) greater than $\pi/2$ or $3\pi/2$. A possible means for this is to dope the crystal with a paramagnetic ion having a spin-lattice relaxation time much shorter than that of the crystal, and a g value equal to that of the crystal at the angle (*e*). At this point, a transition in the doping agent becomes degenerate with the transition in the crystal and thermalization is greatly assisted. Under such conditions, ν_1 does not have to be close to ν_2.

For reasonable rotational speeds, using likely materials, operation at liquid helium temperatures would be required. The size of sample required for maser action is larger in this type of maser than in the static sample type because only a fraction [= (angular width of resonance)/π] of the crystallites contribute to amplification at a given time. This fraction is of the order of 10^{-2} for sodium plutonyl acetate and ν_2 corresponding to maximum g.

In principle, the anisotropic-g maser has some advantages over a three-level continuous maser. The regenerative amplifying bandwidth, which is just the cavity bandwidth, can be made considerably larger than the resonance line width. The power required from the local oscillator for inversion is determined by the resonance line width and is therefore independent of the

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[29] B. Bleaney, "Hyperfine structure in paramagnetic salts and nuclear alignment," *Phil. Mag.*, vol. 42, pp. 441–458; May, 1951.

[30] An alternative mechanism is to fix the crystal in the cavity and rotate a magnetic field of constant amplitude about it by means of suitably phased currents in a coil system.

bandwidth. The local oscillator frequency may be a factor of two or three lower than the signal frequency. Finally, the linear power output is higher because of the larger number of spins contributing to amplification in a given time.

A simple, continuous mechanical microwave generator should be possible using the principle of nonadiabatic field reversal. Paramagnetic material which has spent enough time in a magnetic field to acquire a positive magnetization is transported from that field into a reversed field through a magnet configuration of the general form shown in Fig. 6(a). The electrons experience a time-varying field of the form shown in Fig. 6(b) such as to produce state inversion. The material then passes into a microwave cavity situated in a uniform magnetic field of suitable strength where stimulated emission takes place and microwave oscillation is sustained. On emerging from the cavity the populations of the two states are equal and before the next inverting passage a normal distribution must be attained. One possible means of transport is a disk on the circumference of which the material is mounted so as to pass through the system of fields and the cavity just described. Although the time of transit between the inversion point and the cavity must be much shorter than T_1, the factor likely to determine the minimum rotational speed is the condition for nonadiabatic field reversal, (3). A rate of change of field of the order of 10^7 oersted/sec is required for a line of width 0.1 oersted. This would entail a 6-inch-diameter disk spinning at 4000 rpm through a field gradient, over the range $+1$ to -1 oersted, of 3000 oersted per cm.

Since the minimum rate of change of field is proportional to the square of the line width, materials having inhomogeneously broadened lines may prove most suitable in this application. An interesting property of this device is its ability so convert mechanical energy directly into microwave power with a theoretical efficiency of 50 per cent—the wasted energy going into the "cold" bath, via the lattice, during the preparation of the positive magnetization. The upper frequency limit is determined only by the magnetic field strength available at the cavity and might well extend into the one millimeter region, especially if high g-value materials can be used.

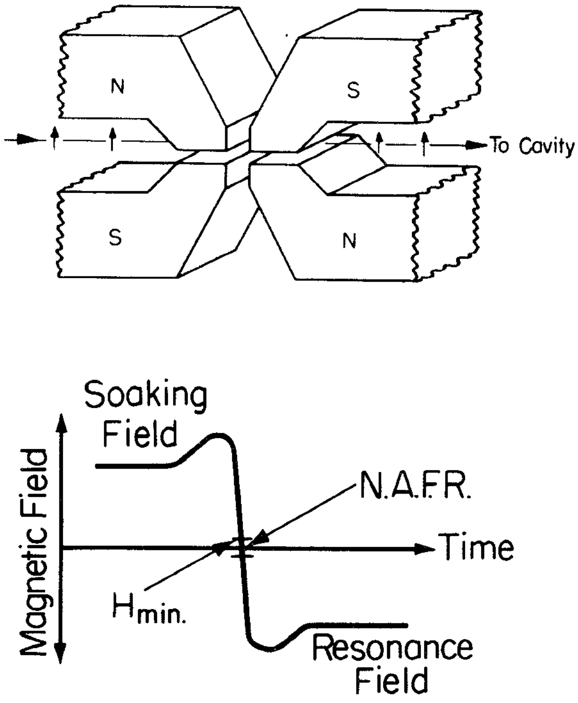

Fig. 6—Schematic magnet configuration (a) and variation of magnetic field as a function of time (b) for continuous state inversion by nonadiabatic field reversal.

Other things being equal, the power output from such a device increases with frequency, and for the disk mentioned above, with $N_2-N_1=10^{17}$ per cm of circumference, would be about 20 milliwatts at a wavelength of 3 mm.

CONCLUSION

Several two-level, solid-state masers are feasible with presently available techniques and materials. A promising application appears to be as low noise amplifiers for radioastronomy and microwave radiometry in which case super-regenerative operation is to be preferred. In principle, a continuous two-level maser having some advantages over the three-level maser is possible using anisotropic materials. Masers are likely to be of use as generators in the millimeter region and even at shorter wavelengths where pulsed fields and intermittent operation are acceptable.