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Microwave Amplification by MASER Techniques

Abstract: A new amplification principle, that of Microwave Amplification by Stimulated Emission of Radiation (MASER), has already demonstrated its potentialities for low-noise, narrow-band amplification.[1] The present note presents an elementary analysis of MASER operation, including its potentiality for broadband, short-transist-time amplification.

Introduction

In *maser* amplification, radiation at microwave and lower frequencies interacts with matter principally by a stimulated absorption or emission of radiation which is proportional to the energy density of the incident radiation. Spontaneous emission, so important at optical and higher frequencies, is a secondary consideration for most microwave situations,[2] including maser applications. Furthermore, whenever thermal equilibrium obtains, the stimulated "absorption or emission" of radiation is always absorption, so that familiar examples of interactions of radiation with matter do not show the emission of energy which is characteristic of masers. Conditions of nonthermal equilibrium differ from those of thermal equilibrium by the possibility that some high-energy states are more highly populated than some low-energy states. Whenever this sort of nonequilibrium can be achieved, there is an enhanced radiation of a frequency ν_0 which "connects" the high (E_2) and low (E_1) energy states

$$\nu_0 = (E_2 - E_1)/h, \qquad (1)$$

in which h = Planck's constant.

This follows because, neglecting spontaneous emission, radiation always so interacts with matter as to tend to equalize the populations of the states it connects. The principle of conservation of energy then requires that if the energy stored in the material be decreased by reducing the population of high-energy states, the radiation energy must be correspondingly increased. Maser amplification achieves this thermal nonequilibrium, either by transient[3,4] or steady-state[1,5] techniques.

Systems capable of maser amplification include molecular beams,[1] donor impurities in silicon,[4] and paramagnetic salts,[5] with the latter two cases confined to operation at low temperatures. These systems are all characterized by low noise temperatures of a few degrees Kelvin under optimum conditions.[6] The bandwidths of current devices vary from a few kilocycles to a few megacycles, with corresponding power handling abilities ranging from a few millimicrowatts to about a milliwatt. Increased bandpasses up to 100 megacycles are feasible and further extension conceivable.

The ammonia-beam maser

The term "maser" was coined in 1955 by C. H. Townes and his co-workers[1] and applied first to a device in which molecular beam techniques were used to achieve thermal nonequilibrium in a beam of ammonia molecules. The energy states involved arise from the phenomenon of inversion, which may be visualized as an oscillation of the nitrogen through the plane of the three hydrogen atoms in NH_3. This oscillation connects two energy states according to Eq. (1). When placed in an electric field, molecules in the two energy states are electrically polarized in opposite directions;[7] consequently, when placed in a nonuniform electric field, these two groups of molecules drift in opposite directions. Use is made of this principle in the selection of a beam of molecules consisting primarily of those in the upper energy state. This molecular beam is then passed through a microwave cavity resonant at the inversion frequency (about 24,000 megacycles). When microwave energy is also passed through the cavity, it induces an emission of radiation at the inversion frequency and a consequent amplification of the microwave energy. Masers based on this principle are currently under investigation at the Watson Research Laboratory. A schematic diagram of a typical ammonia-beam maser is shown in Fig. 1. Since the characteristics of these devices are well described in the literature,[1,6,7,8] they will be listed here only in sufficient detail to enable

comparisons to be made with other types of masers. They are inherently narrow-band, fixed-frequency, low-noise, low-power amplifiers. These characteristics all stem from the molecular beam nature of the device. The bandwidth is essentially the reciprocal of the transit time of the molecular beam through the microwave cavity, which is of the order of a millisecond.

When the device is operated as an oscillator, long-term frequency stability of one part in 10^{10} can be achieved. When operated as an amplifier, it is essentially a low-power preamplifier with maximum output of a few milli-microwatts.

Solid-state masers

The past year has seen the birth of a new type of maser quite different from the ammonia-beam prototype. This is the solid-state maser based on the properties of electron-spin resonance. Because of its newness and the possibility of its application to pulse amplification and switching situations, the solid-state maser will be described in more detail than the ammonia-beam device.

• *A nuclear-resonance pulsed maser*

The development of the electron-spin maser has borrowed heavily from the techniques and ideas of nuclear resonance. Probably the earliest solid-state maser—excepting the "microwave" part of the title — was demonstrated in a beautiful experiment by Purcell and Pound[3] in 1951. They placed a crystal of lithium fluoride in a magnetic field of 6376 oersteds and allowed it to come to thermal equilibrium (a matter of some minutes). The crystal acquired a net magnetization as a result of the partial alignment of the magnetic moments of the spinning lithium and fluorine nuclei in the magnetic field. The subsequent reversal in 0.2 μsec between fields of 100 and -100 oersteds was too rapid for magnetization to follow, and once the fully reversed field of 6376 oersteds was obtained, the magnetization remained in the unswitched, original magnetization state for the same time as that required for achieving the original magnetization, i.e., several minutes. This situation is illustrated in Fig. 2. Initially, in thermal equilibrium at 6376 oersteds, more nuclear moments are aligned with the field than against the field. In the language of Eq. (1), E_1 represents the magnetic energy of a dipole μ aligned with the field H, and E_2 represents the energy for opposed orientations

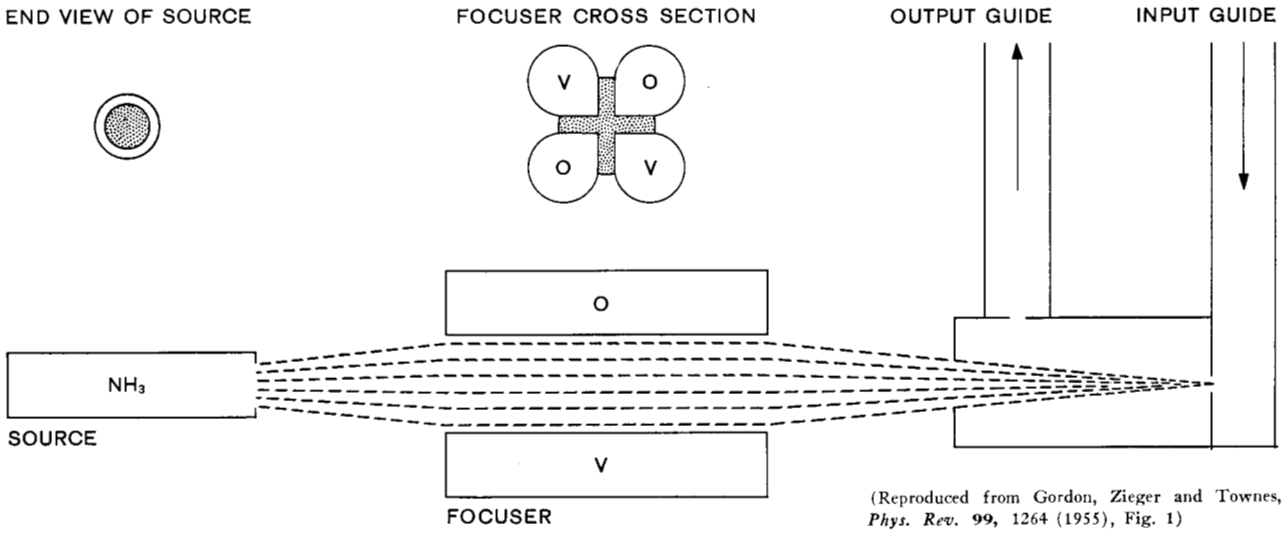
$$E_2 - E_1 = 2\mu H. \tag{2}$$

In thermal equilibruim the population, N_1, of the lower energy state exceeds that, N_2, of the higher energy state. We will denote by primed symbols the nonthermal equilibrium situation obtained by reversing the magnetic field without reversing the magnetization. In this process the energy of the N_1 dipoles aligned with the original field is increased while the N_2 oppositely oriented dipoles suffer a loss in energy, i.e., each spin changes its energy state so that $N'_2 = N_1$, $N'_1 = N_2$ (Fig. 2), $N'_2 > N'_1$. Thus the populations N_2 and N_1 are interchanged with a corresponding net increase of magnetic energy in the spins. Consequently, during the period of nonthermal equilibrium when N_2 exceeds N_1, radiation of a frequency connecting the two states is enhanced. Circuit losses in this case exceed the enhancement, so that there is a reduced loss in r-f power at resonance compared to that at nearby frequencies, rather than an amplification.

Although the spin energies still have a Boltzmann distribution after the field reversal, the average energy then exceeds the average of the available energy states. Purcell and Pound described this situation as corresponding to a "negative temperature" equal in magnitude to the original positive temperature before the field reversal. The interesting thermodynamic properties of negative temperatures have been analyzed by Ramsey.[9a]

The above phenomenon of radiation enhancement by

Figure 1 **Simplified diagram of the ammonia-beam maser.**



(Reproduced from Gordon, Zieger and Townes, *Phys. Rev.* **99**, 1264 (1955), Fig. 1)

nuclear magnetic resonance techniques aroused no technical interest since the effect was much too weak to be of any practical importance.[9b] Recently, however, it has been realized that similar or related techniques may be applied to systems of electron magnetic moments in magnetic fields. Since electron moments are about 1000 times larger than nuclear moments, the effects are large enough to achieve true amplification and to be of practical importance. In all of these devices, applications of Eqs. (1) and (2) show that the resonant frequencies depend on the magnetic fields, i.e., the devices are tunable.

• *A three-energy-level, steady-state maser*

There are a number of current proposals for electron-spin masers, some steady-state, like the ammonia-beam device, and some transient, like the nuclear magnetization reversal device. To date, these devices have been based on paramagnetic systems[4,5] in which the equilibrium magnetization is strongly temperature dependent; consequently, the concept of temperature plays an important role in the analyses. It should be noted at the outset, however, that lags in magnetization reversals also exist in ferromagnetic systems, so that these formal analyses may be too restrictive.

Typical of electron-spin masers is a recent proposal by Bloembergen.[5] The physical embodiment of Bloembergen's scheme, the design principles of which will be described subsequently, is as follows. A coaxial cavity is designed to be resonant at two frequencies, say 1500 mc and some harmonic near 10,000 mc. A cavity volume of 60 cm^3 is chosen — 10 cm long with a 4 cm diameter outer conductor. The large volume is characteristic of the 1500 mc frequency, for which the cavity is a half-wavelength long. The cavity is partly filled with a paramagnetic salt in single-crystal form [$Gd_{.01}La_{.99}(C_2H_5SO_4)_3 \cdot 9\ H_2O$ is one suggestion], immersed in liquid helium and placed in a magnetic field of about 1000 oersteds. Assuming proper design, then, the device will operate as a continuously active amplifier at 1500 mc, provided it is driven continuously by a few milliwatts of 10,000-mc power. Alternatively, the amplifier may be periodically activated by bursts of 10,000-mc power. The power output may approach a milliwatt.

One may visualize the process as one in which the 10,000-mc power input is analogous to the "B" battery power input in an ordinary amplifier which is tuned to operate at 1500 megacycles. There is, however, no cathode — nothing, save the liquid helium baths, that can deteriorate with time. More important, however, is the anticipated low noise temperature of about 4°K. The above numbers are achieved by designing a cavity with a Q (at liquid-helium temperature) of 10,000. This is not a difficult design problem, but it does restrict the bandpass of the amplifier. The amplifier, however, is tunable by simultaneous variations of the magnetic field and the frequency of the microwave driving power.

Let us now consider the principle on which the Bloembergen maser operates. Three unequally spaced energy levels are involved, $E_3 > E_2 > E_1$, connected by frequencies ν_{31}, ν_{32}, and ν_{21} according to relations analogous to Eq. (1) as shown in Fig. 3. In thermal equilibrium, the lower energy levels will be more highly populated: $N_1 > N_2 > N_3$. If, now, radiation ν_{31} (10,000 mc in our example) of sufficient intensity is passed through the material, the populations N_1 and N_3 will approach equality, $N'_1 = N'_3$. Under proper conditions this may result in the population N'_2 exceeding N'_1. When this happens, radiation ν_{21} will then tend to make the populations N'_2 and N'_1 equal, i.e., it will induce emission of radiation at the frequency ν_{21} and consequent amplification of this signal frequency. An operating maser of this design is described in reference 5b.

The achievement of thermal nonequilibrium

It is clear from the examples discussed that masers may be based on a number of different operating principles. None the less, it is desirable to knit the subject together with a few generalizations and simplifications to make some estimates of future trends, potentialities, and limitations of maser operation. In particular, it may be noted that all present solid-state masers have in common the positive feature of low noise and the, for some purposes,

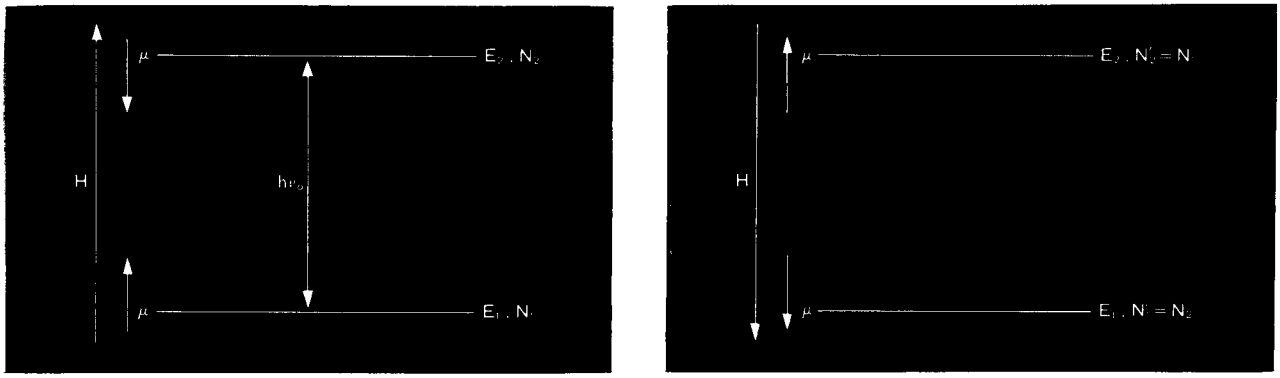


Figure 2 **Energy level diagrams for a magnetic dipole, spin 1/2, in a magnetic field.**
Left, before field reversal. *Right, after field reversal.*

negative feature of comparatively limited band-pass of the order of 1 to 10 mc. Since maser development has been stimulated largely by radar-like applications in which these band-passes are adequate, one must examine the question of whether this restriction is inherent to the device. One may, at this point, anticipate the answer by saying that every increase in band-pass increases the difficulty in attaining thermal nonequilibrium.

The nature of the problem is as follows. When there are only weak interactions among the individual moments, or between the moments and some temperature reservoir (the lattice), the achievement of a magnetization temporarily opposed in direction to the magnetic field is relatively easy, and this "negative temperature" magnetization can be retained for a long period of time. Furthermore, the attainable amplification at resonance, for electron-spin systems, can be high since the resonance is sharp and, in addition, high-Q cavity systems can be used. A straightforward way to increase the band-pass in such a system would be to place the spins in a nonuniform magnetic field, with a consequent distribution in resonant frequencies. This situation occurs naturally for low concentrations of donor impurities in silicon, where the random magnetic fields of Si^{29} nuclei furnish the inhomogeniety in the field. In this approach, since the same number of electron spins are used to amplify over an increased band-pass, the amplification is reduced in proportion to the increase in band-pass. Furthermore, the loaded Q of the cavity must be decreased to utilize the band-pass of the spin system. It is obvious that this approach soon results in an unusually low amplification.

A logical next step is to increase the total number of magnetic electron spins. This may be done both by increasing the volume of the sample and the concentration of spins. The volume is necessarily limited, among other things, by a transit-time restriction, while the increase in spin concentrations results in an increase in the interactions among the individual spins and, to a lesser extent, with the lattice. As a result of these interactions, the attainment of magnetization reversal becomes more difficult although, once attained, the reversal can still be maintained for usable periods of time.

When the band-pass, $2\Delta\nu$, of the spin system is determined by the mutual electron spin interactions, a situation known as homogeneous broadening, the time T_2, in which the spins can approach internal thermal equilibrium, is related to the reciprocal of the band-pass by:

$$T_2 = \frac{1}{2\pi\Delta\nu} . \qquad (3)$$

Here $2\Delta\nu$ is the frequency spread between half-power points of the response curve of the spin system. For a band-pass of, say, one megacycle, this time is a fraction of a microsecond. Current understanding of the problem of achieving magnetization reversal in paramagnetic systems requires that an alteration of magnetic field severalfold larger than the random internal magnetic fields responsible for the band-pass be accomplished in a time less than T_2. Now, Eqs. (1) and (2) result in a proportionality of resonance frequency to magnetic field,

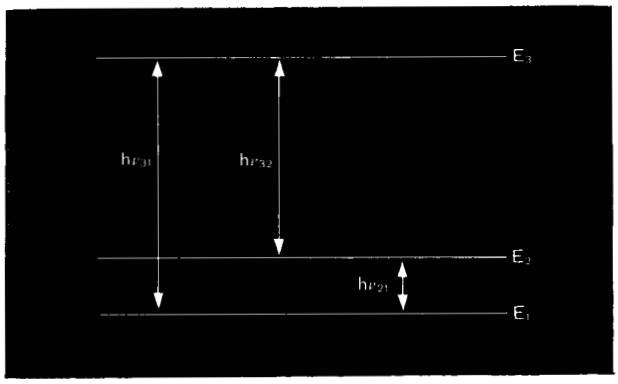


Figure 3 **Energy level diagram for 3-level maser.**

with a corresponding proportionality of the width of the frequency response curve to the random internal magnetic field ΔH. The relations are

$$\begin{aligned} \nu_0 &= \bar{\gamma}H, \\ 1/\pi T_2 = 2\Delta\nu &= 2\bar{\gamma}\Delta H, \\ \bar{\gamma} &= 2\mu/h. \end{aligned} \qquad (4)$$

where $\bar{\gamma} = 2.8$ mc per oersted for free-electron spins and 1.6 kc per oersted for lithium nuclei. Since from a classical point of view, the frequency ν_0 is a precessional frequency of the magnetic moments about the magnetic field, the condition for attainment of magnetization reversal states that the change in magnetic field be accomplished in a time shorter than the precessional period of the spins in the random magnetic fields of their mutual interactions.

The simplest example of this situation is the nuclear magnetization reversal already referred to, where $\Delta\nu$ was about 50 kc, corresponding to $\Delta H = 30$ gauss and $T_2 = 3$ microseconds. For an electron-spin resonance with $\Delta\nu = 1$ megacycle, $\Delta H = 0.36$ gauss and $T_2 = 0.16$ microseconds. Although these figures are feasible, it is clear that a factor of 100 increase in ΔH and decrease in T_2 present technical challenges.

The time T_2 referred to above is not to be confused with the much longer time, T_1, during which thermal nonequilibrium will persist. This latter time is that required for equilibrium between the spins and the lattice. In the LiF example this time was several minutes, while for electron-spin paramagnetism at liquid helium temperature, it is of the order of a millisecond to several seconds. The millisecond magnitudes of T_1 apply to cases where T_2 is in the millimicrosecond range.

There are other techniques for attaining a spin reversal, some of which seem at first glance to violate the generalities of Eq. (4). For instance, instead of reversing the d-c magnetic field, one may reverse the magnetization by a pulse of resonant radiation, a technique introduced by Hahn[10] in obtaining nuclear-resonance spin echoes. The problems look similar, however, when viewed in a cordinate system rotating about the d-c magnetic field at the precessional frequency ν_0. By Larmor's familiar theorem, the motion of the magnetiz-

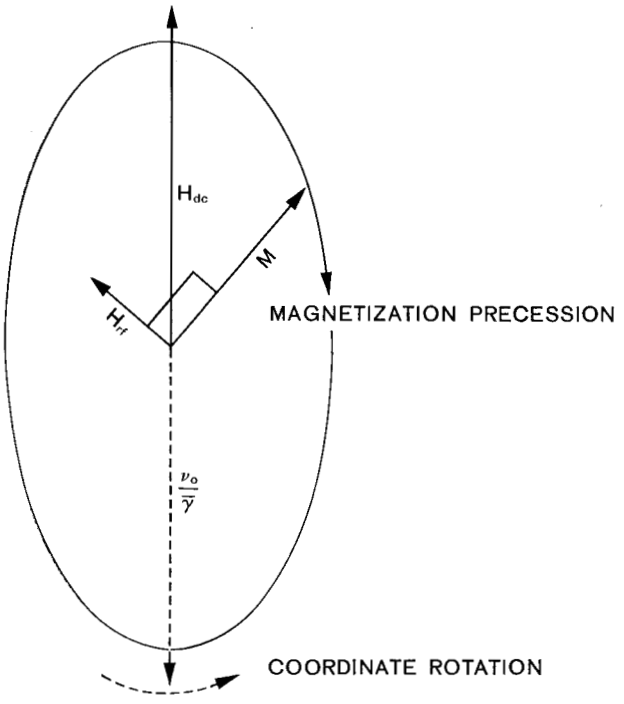


Figure 4 **Magnetization precession in rotating coordinate system.**

ation in the rotating system is just that which would obtain for zero d-c field in a stationary coordinate system. The situation is shown in Fig. 4, where the r-f magnetic field of the radiation pulse, in the rotating coordinate system, is a stationary vector H_{rf} perpendicular to H_{dc}. The magnetization reversal, now, is a half-period precession about H_{rf} which must be accomplished in a time short compared to the precession about the random field ΔH, i.e.,

$$\bar{\gamma}H_{rf} > \bar{\gamma}\Delta H;\ T_{\text{pulse}} = 1/2\bar{\gamma}H_{rf}. \tag{5}$$

One may note that in the spin-echo application, conditions are so chosen that the total magnetization during the "echo" precesses as a unit about the d-c magnetic field direction. Under these conditions there is spontaneous emission of radiation. This is, however, not so in the maser case where, except during application of the r-f pulse, magnetization components in the plane perpendicular to the d-c field have random orientations.

One may analyze similarly the "adiabatic fast passage" technique applied by Combrisson, Honig and Townes[4] to a maser based on the paramagnetism of *p*-donor spins in silicon. Here, the resonance magnetic field is changed a few multiples of ΔH in a time comparable to T_1, not T_2. (A fixed magnetic field and variable frequency is an equivalent procedure.) However, during this change the sample also has to be subjected to a microwave frequency magnetic field greater than ΔH, and the time variation of this field is considerably greater than that of Eq. (4). Such a rapidly changing magnetic field is easily obtained in this case since it corresponds to a steady-state microwave oscillation.

It is also possible to analyze the Bloembergen 3-level maser in the language of Eq. (4). Here the magnetic field in question is that of the microwave driving field. The device, indeed, will work if the driving field is reduced from that of Eq. (4) in the ratio of T_2 to T_1, but the effective bandwidth is correspondingly reduced.

Bandwidth-amplification relations

We may analyze the circuit properties of a paramagnetic substance placed in a resonant cavity by means of the equivalent circuit of Fig. 5 in which the *L-C* tank circuit represents the cavity and the resistances R_O, R_E and R_M are proportional to the power dissipation in, respectively, the cavity walls, the external circuit (useful power) and the magnetic sample. If the sample emits rather than absorbs energy, R_M is negative, amplification occurs when $-R_M > R_O$, and oscillation when $-R_M > R_O + R_E$.

It is convenient to relate the above conditions on R to conditions on Q, the ratio of energy stored in the tank to energy dissipated per cycle in each resistance. These relations then yield, for stable amplification,

$$-Q_M^{-1} > Q_O^{-1} \text{ and } Q_L^{-1} = Q_O^{-1} + Q_E^{-1} + Q_M^{-1} > 0, \tag{6}$$

where Q_L is the loaded Q of the cavity.

We note that Q_M must be a small negative number for broadband amplification.

For paramagnetic substances at temperatures where thermal energies considerably exceed the magnetic energy of Eq. (2), expressions for the magnetic Q in the thermal equilibrium state of positive Q_M have been worked out conveniently so that, at reasonance[11]

$$Q_M = \frac{3k\,TS}{4\pi^2\nu_0 T_2 N_0 \mu^2 (S+1) f}, \tag{7}$$

where f is the filling factor of the cavity, roughly the ratio of paramagnetic salt volume to cavity volume.

In addition to previously defined quantities, k, T, S, and N_0 are, respectively, the Boltzmann constant, temperature, spin, and density of spins. A magnetic field reversal without a magnetization reversal is also described by Eq. (7), with a negative temperature approximately equal in magnitude to the positive temperature before the reversal.

For the simplest substances, those with negligible exchange interactions, the local magnetic fields arise from static dipole-dipole interactions

$$\Delta H \approx \mu / r^3 \approx \mu N_0. \tag{8}$$

More accurate estimates of internal fields are available but Eq. (8) is adequate here. Combining Eqs. (4), (7) and (8) and choosing a typical spin value as $S = \frac{1}{2}$, then

$$Q_M = \frac{kT}{\pi h \nu_0 f} = \frac{kT}{\pi \bar{\gamma} h H f}. \tag{9}$$

Typical values of $T = -4°$, $f = 0.2$ and $\nu_0 = 10{,}000$ mc yield a value of $Q_M = -1.3$. Dielectric or other losses in

the salt have been neglected although in some cases they may be important. Circuitwise they may be included in Q_O.

This Q_M value is amply small to allow a broadband circuit loading. The core of the problem, therefore, is indeed the attainment of the nonequilibrium state — the negative temperature — rather than the inherent amplification potential of the paramagnetic substance. It may be noted that the independence of Q_M on bandwidth is a consequence of choosing the density of spins prescribed by Eqs. (4) and (8) for the bandwidth in question. A 1000-mc bandwidth implies a spin density of the order of 0.5×10^{22} spins per cc, depending on the magnetic moment of the substance chosen. These values are readily attained in fairly concentrated paramagnetic salts.

A feasible 100-mc bandwidth maser

We will consider the requirements posed in attaining a 100-mc band-pass at 10,000 mc by the technique of adiabatic fast passage. The circuit band-pass prescribes $Q_L = \nu_0/2\Delta\nu = 100$. The unloaded Q can easily be made much larger than this, typically $Q_O = 10{,}000$. The power amplification, using a reflection cavity is[5]

$$P_r/P_i = \frac{(\beta-1)^2}{(\beta+1)^2}$$

$$= \frac{(Q_E/Q_O+Q_E/Q_M-1)^2}{(Q_E/Q_O+Q_E/Q_M+1)^2} \approx \frac{(Q_E/Q_M-1)^2}{(Q_E/Q_M+1)^2}, \quad (10)$$

where β is the voltage standing-wave ratio for the cavity tuned to resonance and P_i and P_r are, respectively, the power incident on and reflected from the cavity. A gain of 50 corresponds to a requirement of

$$Q_M = -33, Q_E = 25. \quad (11)$$

The combination of Eqs. (9) and (11) suggests one can reduce the concentration of spins by a factor of 25 from the value given by Eq. (8) corresponding to the 100-mc band-pass. In a uniform magnetic field, this would reduce the band-pass without changing Q_M. However, an inhomogeneity of 35 oersteds in the magnetic field will spread the response over the desired band-pass. There will be a distribution of resonant frequencies, each 4-mc wide, over the 100-mc band-pass. The increased band-pass is achieved at the expense of a corresponding factor of 25 increase in Q_M. The adiabatic fast passage is achieved by tuning a driving frequency over a frequency range of 100 mc (centered at 10,000 mc). The required minimum amplitude of the microwave-frequency magnetic field is given by Eq. (4) with $2\Delta\nu$ the 4-mc bandwidth, i.e., about 1.5 oersteds. Satisfactory operation might require an r-f field of 5 oersteds. The fast passage must be achieved in less than a millisecond (T_1).

The above figures are all quite feasible. Extending the band pass to 1000 mc, however, changes Q_L to 10, Q_M to -3.3 so that the spin concentration is reduced only by a factor of 2.5 from a value initially tenfold that of the 100-mc example. That is, the "diluted" band-pass is now

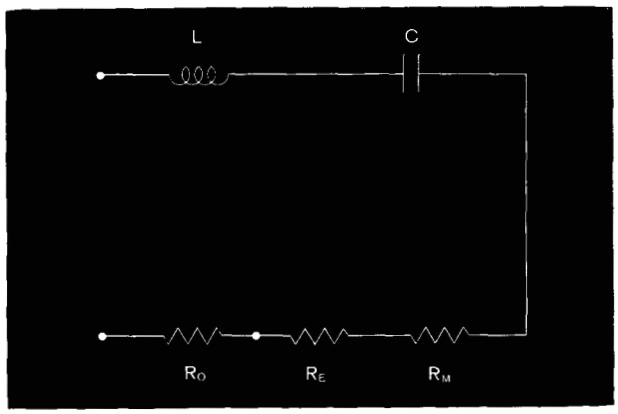


Figure 5 **Equivalent circuit of maser amplifier.**

400 mc, corresponding to a minimum microwave magnetic field of 150 oersteds. The implications of this large driving field will become evident by comparison with a less drastic situation to be discussed in the next section.

It is possible that Bloembergen's 3-level continuously active maser has a somewhat better ultimate broadbanding potential, since the two-resonant-frequency feature may permit a high-Q driving cavity combined with a low-Q amplifying cavity. A single driving frequency may generate a distribution of amplifying frequencies.

Miniaturization, high frequency, and high speed

In other areas, high-speed performance and miniaturization have been found to go hand in hand. It is not surprising, therefore, to find that the same situation holds for masers.

Consider the straightforward implications of Eqs. (4), (5), and (9). Maximum amplification is achieved at the highest frequencies and, since cavity dimensions are small, transit times are also shortest here. Therefore, for a frequency of 100,000 mc the Q numbers in the preceding analysis of a 100-mc bandwidth at 10,000 mc are unchanged, while the field inhomogeneity and driving r-f field are increased to 350 and 50 oersteds, respectively. The volume V_c of a typical cavity would be about 10^{-3} cm^3. Neglecting the variation in Q_M during activation, the input power, applied in short bursts, would be

$$P_i = \frac{\nu H_{rf}^2 V_c}{4Q_E} = 250 \text{ watts}. \quad (12)$$

Conceivably the circuit loading of the cavity could be decreased during the activation period reducing P_i perhaps by a factor of 10. In any case, not more than 10 percent of this power is dissipated in the cavity and sample, and the average power dissipation requirement is smaller. Thus a 0.1-microsecond pulse at a repetition rate of one kilocycle (0.01 percent duty cycle) would be adequate for activation. The resulting average power dissipation in cavity and sample would be 2.5 milliwatts, which would be quite tolerable. A straightforward computation shows that about 1 erg of magnetic energy is fed into the

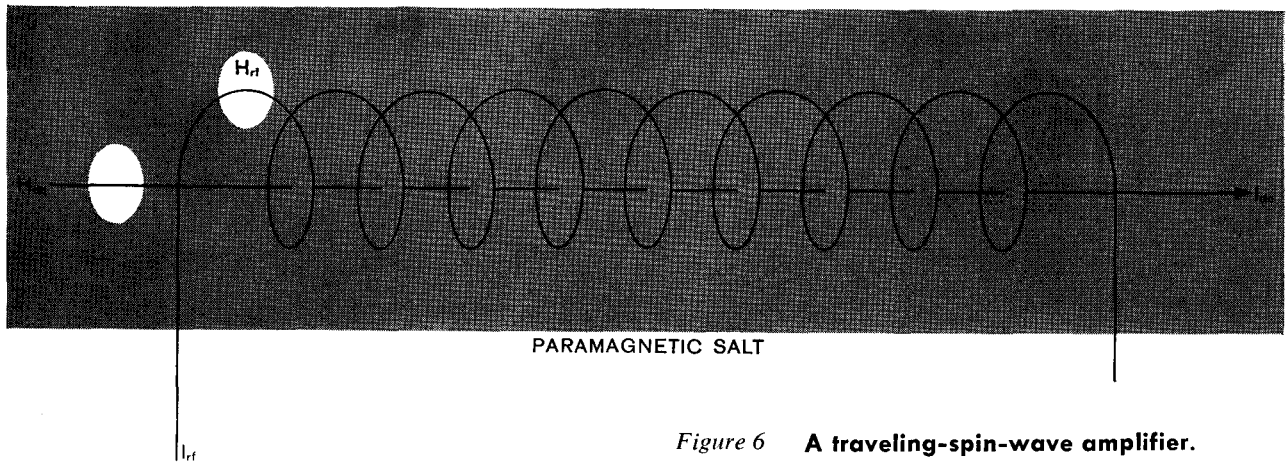


Figure 6 **A traveling-spin-wave amplifier.**

spin-system during each cycle, i.e., an average input of 1 milliwatt. The average available output power, thus, would be a fraction of this — perhaps 200 microwatts — with the remaining energy dissipated in the lattice. For comparison, the noise power $kT(2\Delta\nu)$ at 4° and a 1000-mc band-pass is 5 x 10^{-8} microwatts.

One may note that current magnetrons at 100,000 mc are capable of delivering peak powers of 10 kilowatts so that one magnetron could activate a number of masers. During the 0.1-microsecond pulse either the magnetron must be tuned 1000 mc or the magnetic field changed 350 oersteds. The latter seems feasible by using a small auxiliary solenoid wound around the cavity.

A low-frequency travelling-spin-wave maser

One may approach the question of the suitability of masers to millimicrosecond pulse amplification (no carrier) by trying to design a broadband maser at a center frequency of 1000 mc. A highly speculative approach to this problem would be to achieve an inhomogeneous d-c field of a few hundred gauss as the circular field around a straight wire a few mils in diameter carrying a current of a few amperes. If, now, a helix is wound around the wire, an r-f field traveling along the helix is everywhere perpendicular to the d-c field (see Fig. 6). Just as with a traveling-wave tube or a delay line, a long r-f path is compressed into a relatively short space. If, now, the center wire and helix are both imbedded in a paramagnetic salt at 4°, pulsed changes of current direction in the center wire will periodically activate the amplifier by the Pound-Purcell technique of field reversal without magnetization reversal. The attainable speed of reversal of magnetic field will determine the necessary dilution of the paramagnetic salt. The available gain increases with helix length and decreases with dilution of the salt. A possible result of the necessary compromises in such a design would be a satisfactory amplification at the price of a relatively long transit time, a situation quite analogous to that in conventional traveling-wave tubes.

Summary

The preceding analysis has stressed the bandwidth potentialities and limitations of masers. One may conclude that the distinctive low-noise features of masers may be utilized in circuits up to about 100-mc bandwidth in a fairly straightforward fashion, with corresponding implications for pulsed-carrier-frequency applications. Attainment of broader bandwidth is difficult but conceivable by miniaturization at millimeter wave lengths.

Masers based on paramagnetic resonance may be tuned by variation of the magnetic field. Some designs are continuously active amplifiers; others require a pulsed activation. The latter devices will store their amplifying state for time of the order of a millisecond to several seconds.

Molecular-beam masers have rather different properties. They have bandwidths of a few kilocycles, some devices being tunable by magnetic fields and others not tunable. The latter type are particularly useful as frequency standards and also have low noise figures as amplifiers.

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