A Broadbanded Solid-State Microwave Maser Operating at 77.4°K

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Abstract—This paper considers several aspects of the problem of obtaining solid-state microwave maser action at 77.4°K. A maser cavity, designed to have a large filling factor, high unloaded Q, and tunability over a two per cent range is described. Using this cavity, a study was made of ruby as a maser material at 77.4°K. An important result of this study is the determination of the optimum Cr^{+++} concentration for 77.4°K maser action.

A well-known broadbanding technique was applied to the maser to increase its gain-bandwidth product. Two high-Q microwave cavities spaced three-quarters wavelength apart were placed in front of the maser cavity to produce the broadbanding. The experimental results are given, and the usefulness of this technique as a method of improving maser performance is evaluated. The broadbanded maser had a midband gain of 14.5 dB and a bandwidth of 7.5 Mc/s at a signal frequency of 9.3 Gc/s. Approximately $3\frac{1}{2}$ watts of pump power at 23.4 Gc/s were required.

I. Introduction

In the past, the majority of solid-state microwave masers have been operated at temperatures of a few degrees Kelvin. Maser action is strongest at these very low temperatures because here the population difference between energy levels of the maser material is greatest. It was recognized at an early date that if useful maser action were possible at higher temperatures, the practical difficulties associated with maintaining the maser bath temperature would be greatly alleviated. Ditchfield and Forrester [1] in 1958 reported the first successful operation of a solid-state maser using a coolant other than liquid helium. They saw maser action in ruby at temperature of 56°K using liquid oxygen as the coolant. Shortly thereafter, Maiman [2] succeeded in operating a ruby maser at 77.4°K (liquid nitrogen temperature). Maser action at 77.4°K has since been obtained by several others. Reitböck and Redhardt [3] have reported a ruby maser operative at 90°K.

Although several ruby microwave masers have been operated at 77.4°K, relatively little detailed information is available on their performance. The purpose of this paper is to report in some detail the results of a study [4] of the properties, potentialities, and limitations of microwave maser action at 77.4°K in ruby.

In particular, the following topics are covered. The maser microwave structure, a specially designed microwave cavity with the properties of large filling factor, high unloaded Q, and tunability, is described. This cavity was used to make a study of ruby as a microwave maser material at 77.4°K. Maser action at 9.3 Gc/s was obtained in six different samples of varying chromium (Cr^{+++}) content. These results are described and the optimum Cr^{+++} concentration for maser action at 77.4°K determined. The remainder of this paper briefly describes the use of a conventional broadbanding technique to increase the maser gain-bandwidth product.

Manuscript received September 28, 1964; revised November 20, 1964. This work was sponsored by the U. S. Army Signal Research and Development Lab., Fort Monmouth, N. J., under Contract No. DA 36-039SC-90839. This work was performed at the Stanford Electronics Labs.

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II. The Maser Microwave Structure

A solid-state microwave maser can have either of two forms, traveling wave or cavity. The early experiments of Ditchfield and Forrester [1] and of Maiman [2] verified that much larger pump powers are required when the maser operating temperature is increased. For this reason, the cavity approach was chosen. The smaller size of the paramagnetic sample and the more efficient coupling between pump fields and sample mean that less power is required for the cavity case.

The design chosen for the maser cavity, shown schematically in Fig. 1, is a "single-ended" cavity of the type described by Ammann and Morris [5], [6]. The cavity, which is circular in cross section, consists of two regions, a dielectric-filled (ruby-filled) section and an unfilled section. The dielectric-filled section is bounded by a conducting wall, while the unfilled section is bounded by a movable conducting plunger. Due to the difference in dielectric constants of the two regions, the dielectric region is propagating for low-order waveguide modes while the unfilled region is below cutoff. The resonant frequency of the cavity can be varied by changing the position of the movable plunger.

The microwave cavity of Fig. 1 has several properties which particularly suit it for maser work. 1) It is possible to have frequency tuning (over a limited range) while maintaining a large cavity filling factor. 2) TE and TM modes tune in opposite directions, i.e., as the plunger is pulled out, the frequencies of TE modes decrease while the frequencies of TM modes increase. This fact is useful in mode identification, separation of degenerate modes, and elimination of interference between modes. 3) The cavity has a relatively high unloaded $Q(Q_u)$. 4) For the circular cross section, the field solutions may be found exactly [6]. It is, therefore, possible to obtain exact expressions for cavity filling factor and cavity Q_u and to choose cavity dimensions which maximize these quantities.

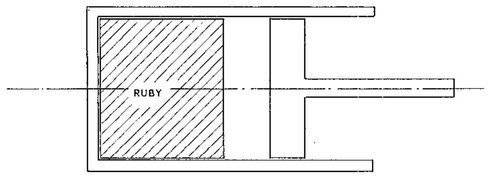

Fig. 1. Maser cavity used for 77.4°K operation.

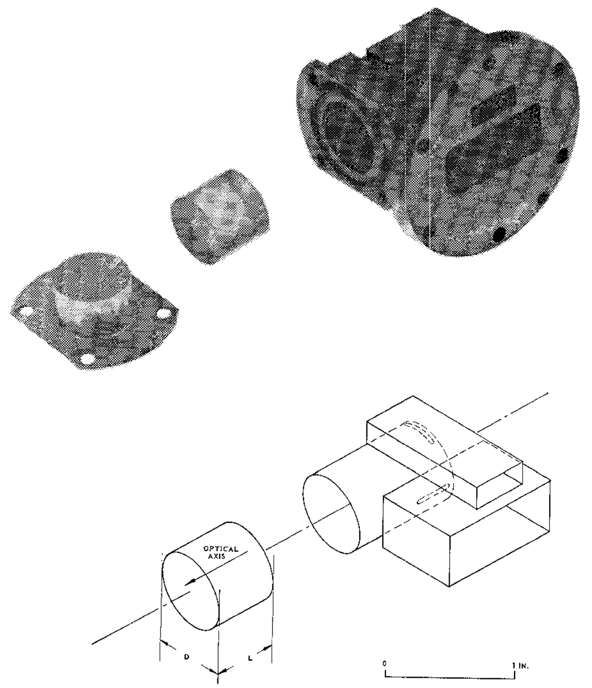

Fig. 2. Practical embodiment of 77.4°K maser cavity.

The practical embodiment of the maser cavity is shown in Fig. 2. The ruby dimensions of $L=0.462$ inch and $D=0.545$ inch were chosen to make the cavity resonant in the TE_{011} mode at the signal frequency of 9.3 Gc/s. The cavity was machined to have a diameter 0.005 inch larger than the ruby, and the interior was lined with teflon sheet 0.002 inch thick. The teflon sheet provided a snug fit for the ruby while ensuring that the cavity surface was not scratched. Coupling of signal and pump energy into the cavity was accomplished by means of slots in the cavity walls, as shown in Fig. 2.

In order to ensure that liquid nitrogen did not enter the cavity, the entire structure was made vaccum tight. A fixed, rather than movable, plunger was bolted to the cavity, the vacuum seal being provided by a rubber O-ring. The cavity was still tunable in the sense that the frequency could be changed by using a plunger of different length. Several plungers of various lengths were constructed.

Several measurements were made to verify the predicted microwave performance of the ruby-filled cavity. The cavity had a tuning range of 210 Mc/s and an unloaded Q of approximately 4500 at room temperature and 7500 at 77.4°K. It was not possible to make an absolute measurement of the cavity filling factor, but it is estimated that the calculated value of 0.85 was closely approached. Although this cavity was designed specifically for use in a 77.4°K maser, its properties also made it useful for other paramagnetic resonance work [7].

III. Ruby as a Microwave Maser Material at 77.4°K

The strength of maser action in ruby is highly dependent upon the chromium concentration. Therefore, an important question at any operating temperature is that of determining the chromium concentration that results in strongest maser action. Tabor has studied chromium concentration optimization for maser operation from 1.5° to 4.2°K at 1.35 Gc/s [8] and from 1.5° to 20°K at 5.6 Gc/s [9]. At 77.4°K, very little has been done previously on this problem. Very likely the most important results of this paper are a determination of the chromium concentration of ruby that gives strongest maser action at 77.4°K and a study of the paramagnetic processes that determine this optimum concentration.

The achievement of microwave maser action at higher temperatures is made difficult by two factors. Population inversions of the paramagnetic energy levels are smaller at higher temperatures, and, in fact, are inversely proportional to the absolute bath temperature. In addition, spin-lattice-relaxation times decrease as the bath temperature is increased. This means that considerably larger amounts of pump power are required for higher-temperature maser operation.

The strength of maser action will be described by the magnetic $Q(Q_m)$ of the maser, defined as

$$Q_m = \frac{\omega_0(\text{energy stored in cavity})}{(\text{power emitted by paramagnetic material})} \tag{1}$$

The stronger that maser action is, the smaller Q_m will be. We may rewrite Q_m in terms of cavity and paramagnetic material parameters as

$$Q_m = \frac{2\mu_0}{\hbar\gamma_0^2 g(f_0) I \left(\frac{N}{n}\right) \frac{hf_s}{kT} \eta\sigma^2} \tag{2}$$

where

μ_0 = free-space permeability
$\hbar$ = Planck's constant/2π
$g(f_0)$ = value of lineshape function at line center
I = inversion ratio of maser
N = number of paramagnetic ions per unit volume of maser material
n = number of energy levels in the paramagnetic material (four for ruby)
f_s = frequency at which maser amplifies
k = Boltzmann's constant
T = maser bath temperature (°K)
η = filling factor of maser cavity
σ^2 = maximum possible value which transition-probability tensor can have when linearly polarized H fields are present

Equation (2) shows explicitly the dependence of Q_m upon the bath temperature T.

In order to study the effect of chromium concentration upon maser action, six ruby samples of different chromium concentrations were obtained. The chromium concentration (wt. of Cr^{+++}/wt. of Al_2O_3) of the six samples was found from spectrographic and chemical analyses to be (nominally) 0.021 per cent, 0.046 per cent, 0.077 per cent, 0.14 per cent, 0.34 per cent and 0.40 per cent. It should be emphasized that these, at best, represent approximate values for the chromium concentration of the rubies. X-ray spectrographic techniques which were used to analyze one of the rubies in detail [10] showed that the chromium ion density varied both microscopically and macroscopically throughout the sample.

Using the maser cavity described in Section II, maser action was obtained at 77.4°K with each of the ruby samples. The maser was operated at the "double-pump" point [11] $\theta=54.7°$ with a signal frequency of 9.3 Gc/s and a pump frequency of 23.4 Gc/s. The measured strength of maser action is plotted as a function of chromium concentration in Fig. 3. We see that the strength of maser action increases with increasing chromium concentration until an optimum value of about 0.20 per cent is reached. The strength of maser action then falls off rapidly as chromium concentration is increased further. It is important to note that while 0.20 per cent is approximately the optimum chromium concentration at 77.4°K, the optimum at 4.2°K is approximately 0.04 per cent [9]. Thus it is possible to use considerably higher chromium concentrations at 77.4°K than at 4.2°K. This increase in N helps to partially offset the increase in T in (2) resulting from operation at 77.4°K. Of the six rubies measured, the 0.14 per cent ruby produced strongest maser action, giving a Q_m of 1250.

The factors responsible for the shape of the curve in Fig. 3 were investigated experimentally by determining the concentration dependence of the various quantities in (2). Since $1/Q_m$ is directly proportional to N, we would expect the curve of Fig. 3 to be a straight line, provided no other terms of (2) are concentration dependent. The departure from a straight line was found to be due to the concentration dependence of the inversion ratio I and the paramagnetic resonance linewidth.

A. Inversion Ratio

The inversion ratio I is the ratio of the population difference of the signal energy levels while the maser is being pumped to the population difference of the same levels at thermal equilibrium. At the double-pump point with the pump transitions saturated, the inversion ratio is given by

$$I=\left[\frac{2w_{14}+w_{34}+w_{12}}{w_{14}+w_{34}+w_{12}+w_{23}}\right]\frac{f_{\text{pump}}}{f_{\text{signal}}}-1 \qquad (3)$$

where the w's are relaxation transition probabilities. Equation (3) is calculated from the rate-equation approach and assumes that all transitions are either stimulated transitions or spin-lattice-relaxation transitions. Since (3) depends upon $f_{\text{pump}}/f_{\text{signal}}$ and the relative sizes of the w's, it appears at first that inversion ratio should be independent of chromium concentration. The measured results of Fig. 4 show this to be true for small chromium concentrations, but the inversion ratio decreases rapidly for larger concentrations. This decrease is due to cross-relaxation processes which (3) does not consider.

Cross relaxation [12]–[14] is a process whereby energy is exhanged directly between neighboring paramagnetic ions. This process is strongest at high concentrations, since the probability of a cross relaxation is greater the closer the neighboring ions. When cross relaxations occur, the energy-level population distributions are altered from those distributions that result when only thermal spin-lattice relaxation and stimulated transitions occur. At high enough chromium concentrations, the energy-level distributions are determined *primarily* by cross relaxation, and it becomes difficult or impossible to maintain a population inversion in the spin system. Thus, maser action becomes weak (or disappears) above a certain concentration, as the data of Fig. 4 verify.

It is important to explain what is meant by "high enough" chromium concentrations. The important factor in determining the strength of cross-relaxation processes is the relative size of cross-relaxation transition probabilities and spin-lattice-relaxation transition probabilities. Cross-relaxation transition probabilities are highly dependent upon concentration, increasing with higher concentrations. Spin-lattice-relaxation transition probabilities, on the other hand, are less strongly concentration dependent but highly dependent upon the bath temperature. Increasing the bath temperature from 4.2°K to 77.4°K will increase the spin-lattice-relaxation transition probabilities by approximately 500 times [15]. For this reason, it is possible to obtain maser action with higher chromium concentrations at 77.4°K than can be used at 4.2°K.

Returning to the experimental results shown in Fig. 4, we note that for small chromium concentrations, the inversion ratio was constant, having a value of about 1.15. This value agrees reasonably well with the value of 1.00 found by Morris [16] for the same operating point at 4.2°K but is considerably less than the value of 2.7 reported by Haddad and Paxman [17]. Since the inversion ratio was constant for low concentrations, it is believed that cross relaxation does not affect the inversion ratio for concentrations below 0.06 per cent.

Above 0.06 per cent, the inversion ratio begins to decrease, falling off rapidly above 0.15 per cent. This accounts for the decrease in strength of maser action at high Cr^{+++} concentrations. It is of interest to note that strongest maser action (minimum Q_m) occurs at a con-

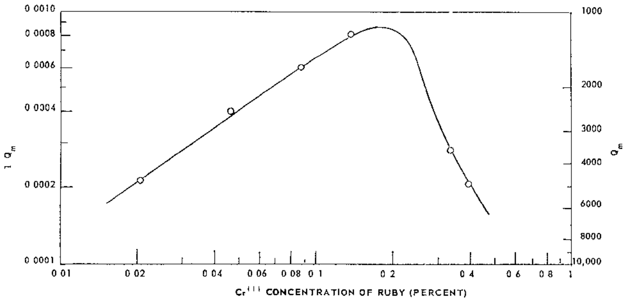

Fig. 3. Strength of maser action as a function of chromium concentration at 77.4°K.

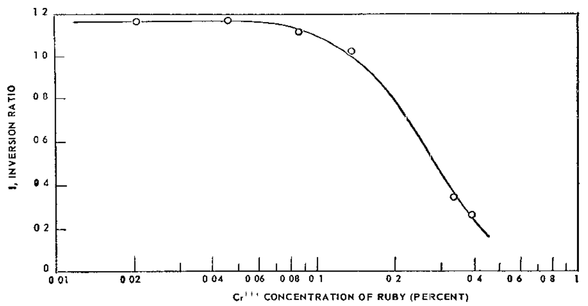

Fig. 4. Measured maser population-inversion ratio as a function of chromium concentration at 77.4°K.

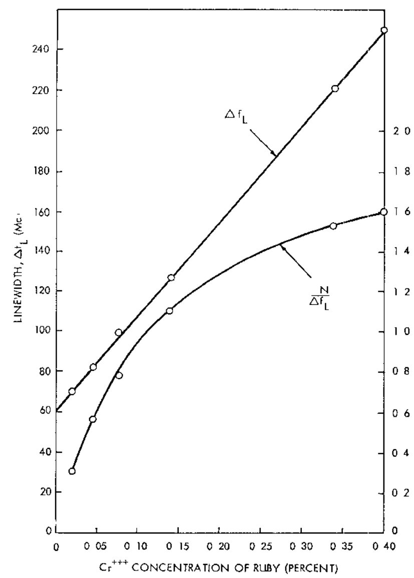

Fig. 5. Ruby linewidth as a function of chromium concentration.

centration for which cross-relaxation processes have already begun to decrease the inversion ratio. At the optimum chromium concentration of 0.20 per cent, the inversion ratio has fallen from 1.15 to 0.80. The increase in N, however, is more than enough to make up for this decrease. Above this concentration, the inversion ratio decreases more rapidly as N increases, and, consequently, the strength of maser action falls off rapidly.

The optimum chromium concentration will depend upon the particular operating point in question. Cross-relaxation processes, which determine the maximum

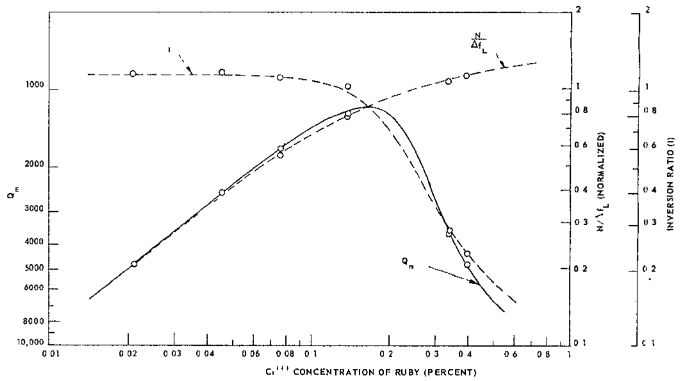

Fig. 6. Concentration dependence of maser action at 77.4°K and the factors that determine its strength.

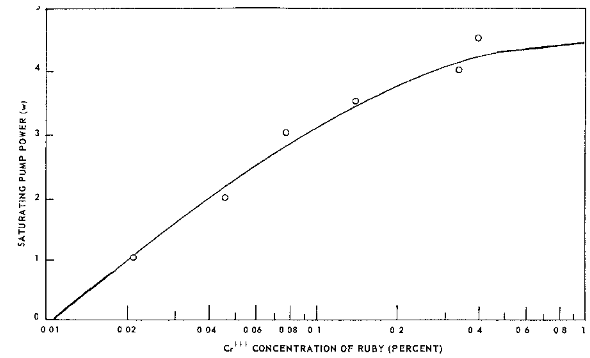

Fig. 7. Saturating pump power as a function of chromium concentration for maser action at 77.4°K.

concentration, differ from operating point to operating point. Thus, there will probably be a different optimum chromium concentration for every operating point, although the variation may well be small. The double-pump point is a point of particular importance since a relatively large inversion ratio is obtainable there with a reasonable pump frequency.

B. Paramagnetic Resonance Linewidth

The term $g(f_0)$ of (2) is also dependent upon chromium concentration. Measurements of the paramagnetic resonance linewidth were made on the six ruby samples to examine the effect of this term upon the strength of maser action. The amplitude of the center of the paramagnetic resonance line is denoted by $g(f_0)$. Since $g(f)$ is normalized so that

$$\int_0^\infty g(f)df = 1 \tag{4}$$

the width and height of a resonance line are not independent. For a Lorentzian lineshape, it can be shown that

$$g(f_0) \cdot \Delta f_L = \frac{2}{\pi} \tag{5}$$

where Δf_L is the Lorentzian linewidth. Substituting for

$g(f_0)$ in (2), we then obtain

$$Q_m = \frac{\mu_0 \pi}{\hbar \gamma_0^2 \left(\frac{1}{\Delta f_L}\right)\left(\frac{N}{n}\right) I \frac{hf_s}{kT} \eta \sigma^2} \tag{6}$$

It is well known that Δf_L increases as the chromium concentration of ruby is increased. Relatively little quantitative data are available, however, to determine the extent of this increase. Measurements were made of Δf_L for the six ruby samples under study. The results are shown in Fig. 5, where Δf_L and $N/\Delta f_L$ are plotted as functions of chromium concentration.

As the concentration approaches zero, the linewidth Δf_L is seen to approach a value of 60 Mc/s. As concentration is increased, Δf_L increases linearly. These results agree quite well with those obtained by Strandberg [18] and Maiman [2].

Figure 6 summarizes the effects of inversion ratio and paramagnetic resonance upon Q_m. Plotted on the same graph are curves of Q_m, I, and $N/\Delta f_L$ as a function of chromium concentration.

C. Pump Power

A major difficulty and disadvantage of maser operation at higher temperatures is the relatively large amount of pump power required for saturating the pump transitions. Since the pump frequency often falls in the upper microwave frequency range, microwave tubes which can supply the necessary power are not always readily available. Hence, it is of practical importance to determine the pump power required for maser action at 77.4°K.

The saturating pump power was measured for the six ruby samples and is shown in Fig. 7. The pump power represents the pump power entering the maser cavity when saturation occurs; some of this power is dissipated as cavity losses.

The results show that the ruby of 0.14 per cent concentration (the ruby which is nearest to optimum) requires about $3\frac{1}{2}$ watts pump power for complete saturation. This power, although large, is not prohibitive. Since no effort was made to design the maser cavity for minimum pump-power consumption, this figure can probably be lowered considerably by careful design. To minimize the required pump power, one should 1) choose a pump mode which has maximum filling factor and maximum unloaded Q, 2) ensure that the pump resonance is on the center of the paramagnetic resonance line, and 3) obtain critical coupling between the pump waveguide and the cavity.

It is of passing interest to note that maser action at 77.4°K was obtained using the 0.021 per cent ruby with pump powers as low as 20 mW. At these low power levels, the pump transitions were not saturated, of course, but the pump power was sufficient to produce inversion.

D. Maser Noise Temperature

Since the importance of microwave masers is due primarily to their low-noise amplification properties, the question of maser noise at a bath temperature of 77.4°K is a pertinent one. Direct noise measurements were not made, but the noise temperature is calculated here using measured values of the maser's magnetic Q, unloaded Q, and inversion ratio. The calculation is performed using a formula due to Maiman [2] which gives the noise temperature (T_e) of a reflection-cavity maser in terms of the magnetic Q, the maser power gain (G), the unloaded Q of the maser cavity (Q_u), the magnitude of the spin temperature (T_s) of the signal transition, and the bath temperature (T)

$$T_e = \left[\frac{G-1}{G}\right]\left[\left(\frac{Q_m}{Q_u - Q_m}\right)T + \left(\frac{Q_u}{Q_u - Q_m}\right)T_s\right] \tag{7}$$

If we substitute into (7) the measured values of $G=26.9$, $Q_m=1250$, $Q_u=7500$, $T=77.4$°K, and $T_s=T/I=75.9$°K we calculate a maser noise temperature of 105°K.

This calculated maser noise temperature is certainly not the lowest possible noise temperature for a 77.4°K maser. Rather, it represents the noise temperature for this particular maser operating at the double-pump point with ruby as the maser material. This figure can probably be lowered considerably by the use of other operating points and perhaps the use of other maser materials.

IV. Broadbanding the Maser

With the 0.14 per cent ruby sample, the maser had a gain bandwidth product of 12.5 Mc/s. While this is adequate for some applications, the maser would be more useful if a larger gain-bandwidth product could be obtained. A broadbanding technique was applied to the maser to increase its gain-bandwidth product. The broadbanding involved no particularly new ideas, but the technique and results are described to show the capabilities and limitations of a 77.4°K maser.

Several different techniques have been used by various workers to increase the gain-bandwidth product of cavity masers operating at liquid-helium temperatures. The efforts at broadbanding a cavity maser may be divided into two groups:

1) Schemes which use additional ruby-filled (active) microwave structures to produce the broadbanding.
2) Schemes which use additional passive microwave structures to produce the broadbanding.

Among broadbanding schemes of the first type, Goodwin [19] has achieved increased gain-bandwidth products for a reflection cavity maser by coupling together two ruby-filled cavities in series. Series-coupled ruby-filled cavities have also been used to increase the gain-bandwidth product of transmission (two-port) masers [19]–[21]. In addition, Nagy and Friedman

[22] have reported large gain bandwidths for a reflection maser which uses a configuration of two ruby reflection cavities in parallel at the end of a waveguide.

Several broadbanding schemes of the second type have also been tried. Cook, et al. [23] have used a resonant coupling plate immediately preceding the maser cavity to provide broadbanding, while Kyhl, et al. [24], have placed a resonant microwave cavity in front of the maser cavity. Kyhl, et al., have considered and, in fact, made use of the ruby paramagnetic resonance linewidth in their broadbanding and have obtained maser bandwidths exceeding the ruby linewidth. All the previously mentioned broadbanding schemes were applied to masers operating at a bath temperature of liquid helium.

In general, the broadbanding techniques which use active rather than passive broadbanding structures seem capable of giving the greatest improvement in maser gain bandwidth. Nonetheless, a passive scheme was chosen to broadband the 77.4°K maser. This choice was made primarily in the interest of keeping the required maser pump power to a minimum. Since a single ruby-filled maser cavity needs several watts of pump power to produce saturation at 77.4°K, it was felt that the presence of several ruby-filled cavities might make the maser impractical to operate.

A. Equivalent Circuit of Broadbanded Maser

The problem of broadbanding a negative-resistance reflection amplifier has been studied by several workers [25]–[30]. One of these techniques [31] was used in a straightforward manner to carry out the design of the broadbanding network. The low-pass equivalent circuit for the 77.4°K maser with two external broadbanding elements is shown in Fig. 8. The elements C_1 and $-R_m$ are associated with the maser cavity and their values are, therefore, fixed. The elements L_2 and C_3 denote broadbanding components whose values can be chosen to produce the desired response. The value of Z_0 will depend on the maser midband gain. The impedance level of the circuit has been normalized so the load $-R_m$ has a value of -1 ohm.

The values of L_2 and C_3 were calculated to give a Chebyshev response with 1-dB ripple for a midband voltage gain of 5.19. Explicit formulas for L_2, C_3, and Z_0 may be found in Ammann [4].

B. Microwave Form of Broadbanding Elements

The problem of obtaining bandpass microwave components corresponding to the low-pass elements L_2 and C_3 is a familiar one from microwave filter theory. Two common methods for realizing such a bandpass ladder network are 1) to use direct-coupled resonators [32], [33] or 2) to use quarter-wave-coupled resonators [34], [35]. For this application, the quarter-wave-coupled resonator approach was chosen (with the minor modification that the resonators were spaced three-quarters instead of one-quarter wavelength apart).

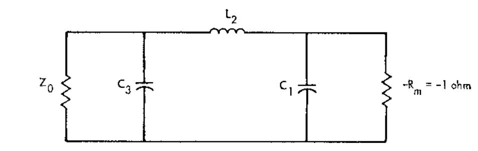

Fig. 8. Low-pass equivalent circuit for maser with two broadbanding elements.

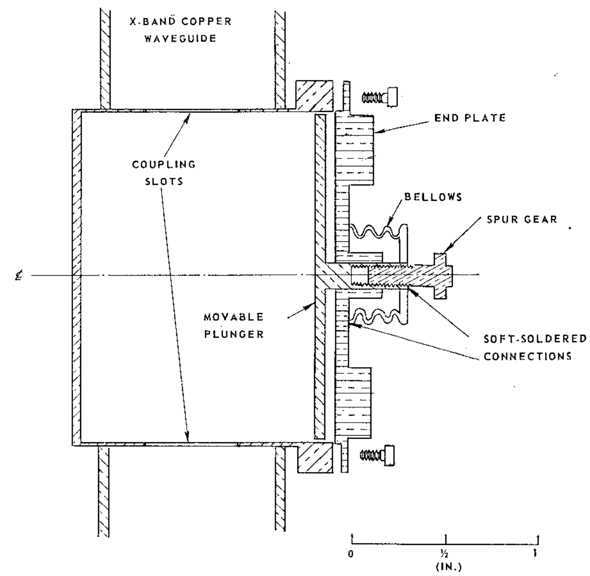

Fig. 9. Cross section of broadbanding cavity.

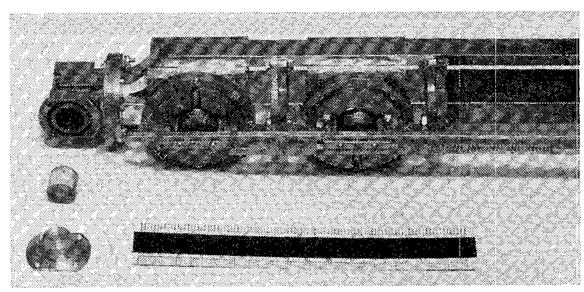

Fig. 10. Assembled maser and broadbanding cavities.

A circular-cylindrical cavity operating in the TE_{011} mode was chosen as the type of resonator to be used. The cavity design is shown in Fig. 9. The cavity, movable plunger, end plate, and connecting waveguides were made of copper. During operation, the broadbanding cavities were immersed in the liquid nitrogen bath. This necessitated the use of a bellows to allow frequency tuning while maintaining a vacuum-tight seal. The unloaded Q of this cavity was measured at 77.4°K and found to be 18 000. The assembled broadbanded-maser structure is shown in Fig. 10, where the maser cavity plus the two broadbanding cavities can be seen.

C. Broadbanded Maser Experiments

The following conditions apply to the experiment to be discussed: 1) the maser was operated at a bath temperature of 77.4°K, 2) the 0.14 per cent ruby sample

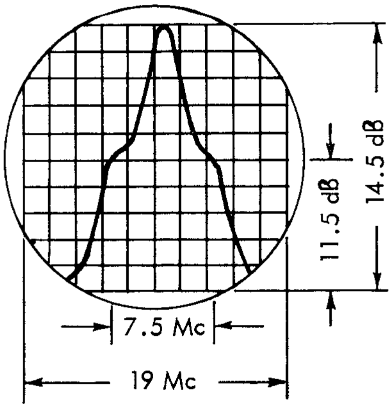

Fig. 11. Experimental broadbanded-maser results showing power output as a function of frequency.

was used, 3) the maser signal frequency was 9.3 Gc/s and the pump frequency was 23.4 Gc/s, and 4) two broadbanding cavities were placed in front of the maser cavity.

The broadbanding-cavity coupling slots were adjusted to give loaded Q's corresponding to the calculated values of L_2 and C_3. The maser response obtained is shown in Fig. 11. The response is seen to depart somewhat from the desired 1-dB Chebyshev response. Additional experiments were performed using slightly altered values of broadbanding-cavity coupling in an attempt to improve the results. In each case, the results were comparable to or less satisfactory than those shown in Fig. 11. The maser response was found to be very sensitive to changes in the coupling or resonant frequency of the broadbanding cavities.

Even though the desired response shape was not achieved, the broadbanding technique succeeded in increasing the maser bandwidth. The results of Fig. 11 show a midband gain of 14.5 dB and 3-dB bandwidth of 7.5 Mc/s. For the same midband gain, the unbroadbanded maser had a 3-dB bandwidth of 2.9 Mc/s. The 7.5-Mc/s bandwidth agrees reasonably well with the predicted bandwidth of 9 Mc/s.

It is believed that one or more of the following factors were responsible for the deviation of the response curve from an ideal Chebyshev shape:

1) Losses in the broadbanding cavities affect the shape of the maser response. The effect of these losses upon the maser midband gain was analyzed in detail [4]. The results show that losses can change the midband gain significantly, particularly for masers with large midband gains. By a judicious choice of the maser midband gain and the desired response shape, it was possible to make the midband gain the same for the broadbanded and unbroadbanded cases. Calculations were not made, however, to determine the effect of losses upon the rest of the maser response.
2) The paramagnetic resonance linewidth, neglected in the broadbanding network design, may be responsible for some of the "falling off" of the response edges. To include the effect of the linewidth, one should use the negative L and C discussed by Kyhl [24], [36].
3) Internal reflections at various small discontinuities within the experimental setup may have altered the response shape.

V. Conclusions

Several aspects of the problem of obtaining solid-state microwave maser action at 77.4°K have been considered.

An experimental study was made of ruby as a maser material at 77.4°K. One of the objects was to study the effect upon the maser performance of varying the Cr^{+++} concentration. It was found that a Cr^{+++} concentration of about 0.20 per cent (by weight) resulted in the maximum gain-bandwidth product for operation at the double-pump point. This concentration does not give minimum noise, however, since cross-relaxation processes have begun to degrade the maser population-inversion ratio.

A broadbanding technique was applied to the 77.4°K maser in an attempt to increase its gain-bandwidth product. The technique consisted of placing appropriately designed resonators between the maser cavity and the signal source. A broadbanding structure utilizing two circular-cylindrical cavities spaced three-quarter wavelength apart was designed, built, and tested. The maser 3-dB bandwidth was increased $2\frac{1}{2}$ times by the broadbanding technique, although the desired Chebyshev response shape was not fully realized during the experiments which were performed. The resulting device had a midband gain of 14.5 dB and a 3-dB bandwidth of 7.5 Mc/s. The following conclusions may be stated about the use of this technique for increasing a maser's gain-bandwidth product.

This technique can be used to increase the bandwidth of a maser by factors of perhaps two to five, depending upon the maser midband gain, the number of broadbanding elements used, the response shape chosen, etc. Larger increases are not obtainable by this or any other technique that uses only passive broadbanding elements. If larger increases are desired, some technique that uses active broadbanding elements should be used.

The number of broadbanding cavities used should probably not exceed two or at most three, because the additional complexity and losses introduced will not be justified by the additional increase in bandwidth. The greatest improvement in bandwidth is obtained from the first broadbanding element, with the improvement then decreasing with the addition of each additional element. Considerable care should be taken in designing and constructing the broadbanding resonators, for the maser response is critically dependent upon their performance and adjustment. If this technique is applied to a maser operating at liquid helium temperature, the paramagnetic resonance linewidth should be taken into consideration when designing the broadbanding network. At higher temperatures, the resonance linewidth may or may not need to be considered. Each case should be considered individually.

At liquid nitrogen temperature, this broadbanding technique should probably not be attempted on masers with midband gains greater than 25 or 30 dB. At these high gains, losses in the broadbanding cavities can change the maser midband gain greatly, thereby completely distorting the maser response. At liquid helium temperatures, however, the broadbanding cavity losses will be considerably reduced, thereby enabling the technique to be used for higher values of midband gain. It should be kept in mind, however, that the higher the gain, the more critical the adjustments of the broadbanding cavities become.

As stated before, if large increases in maser gain-bandwidth products are to be obtained, some type of broadbanding that uses active broadbanding elements must be used. However, at liquid nitrogen temperature, the use of additional ruby-filled cavities is limited by the large amounts of pump power needed for saturation. The following approach is, therefore, suggested as one worthy of investigation. In a single cavity resonator there are an infinite number of modes; by properly designing a cavity, a number of the modes can be made degenerate in frequency. By so doing, it is possible to make a single cavity act like a chain of coupled cavities. It is suggested that by making the maser cavity resonant in more than one mode at the amplifying frequency one might broadband the maser. The noise properties and resulting gain-bandwidth product of such a cavity maser would be of interest.

Acknowledgment

The author wishes to thank Prof. A. E. Siegman for his support and guidance throughout the course of this work. Also acknowledged is the skilled assistance provided by L. W. Dague and G. H. deWerk in construction of the microwave structures. In addition, thanks are extended to R. R. Dils, who performed the X-ray microanalysis of the ruby sample.

References

[1] Ditchfield, C. R., and P. A. Forrester, Maser action in the region of 60°K, *Phys. Rev. Lett.*, vol 1, Dec 1958, pp 448–449.
[2] Maiman, T. H., Maser behavior: temperature and concentration effects, *J. Appl. Phys.*, vol 31, Jan 1960, pp 222–223. See also Maiman, T. H., Temperature and concentration effects in a ruby maser, in *Quantum Electronics*. New York: Columbia University Press, 1960.
[3] Reitböck, H., and A. Redhardt, A molecular amplifier for an operating temperature of 90°K, *Z. Naturforsch.*, vol 17a, Feb 1962, pp 187–188.
[4] Ammann, E. O., A broadbanded solid-state microwave maser operating at liquid nitrogen temperature, Rept SEL-63-017 (TR No. 155-6), Stanford Electronics Labs., Stanford, Calif., Apr 1963.
[5] Ammann, E. O., and R. J. Morris, Tunable, dielectric-loaded microwave cavities capable of high Q and high filling factor, *IEEE Trans. on Microwave Theory and Techniques*, vol MTT-11, Nov 1963, pp 528–542.
[6] ——, Tunable, dielectric-loaded microwave cavities capable of high Q and high filling factor, Rept SEL-63-012 (TR No. 211-4), Stanford Electronics Labs., Stanford, Calif., May 1963.
[7] Ammann, E. O., Experimental verification of calculated matrix elements of the magnetic moment of ruby, *Appl. Phys. Lett.*, vol 1, Sep 1962, pp 1–2.
[8] Tabor, W. J., Optimization of chromium concentration in ruby, *L*-band, Second Quarterly Progress Rept, Solid-State Maser Research, Bell Telephone Labs., Murray Hill, N. J., Dec 1960.
[9] ——, Optimization of chromium concentration in ruby, First Quarterly Progress Rept., Solid-State Maser Research, Bell Telephone Labs., Murray Hill, N. J., Sep 1960.
[10] Dils, R. R., G. W. Martin, and R. A. Huggins, Chromium distribution in synthetic ruby crystals, *Appl. Phys. Lett.*, vol 1, Dec 1962, pp 75–76.
[11] Kikuchi, C., J. Lambe, G. Makhov, and R. W. Terhune, Ruby as a maser material, *J. Appl. Phys.*, vol 30, Jul 1959, pp 1061–1067.
[12] Bloembergen, N., S. Shapiro, P. S. Pershan, and J. O. Artman, Cross-relaxation in spin systems, *Phys. Rev.*, vol 114, Apr 1959, pp 445–459.
[13] Hirono, M., On the theory of cross relaxation in maser materials, *J. Phys. Soc. Japan*, vol 16, Apr 1961, pp 766–776.
[14] ——, On the theory of cross relaxation in maser materials, II. Harmonic Spin Coupling, *J. Phys. Soc. Japan*, vol 17, May 1962, pp 788–795.
[15] Pace, J. H., D. F. Sampson, and J. S. Thorp, Spin-lattice relaxation times in ruby at 34.6 Gc/s, *Proc. Phys. Soc. (London)*, vol 76, Nov 1960, pp 697–704.
[16] Morris, R. J., R. L. Kyhl, and M. W. P. Strandberg, A tunable maser amplifier with large bandwidth, *Proc. IRE (Correspondence)*, vol 47, Jan 1959, pp 80–81.
[17] Haddad, G. I., and D. H. Paxman, Traveling-wave maser experiments using ruby at X band, *IEEE Trans. on Microwave Theory and Techniques*, vol MTT-12, Jul 1964, pp 406–414.
[18] Strandberg, M. W. P., Ruby linewidth, Rept 10, Research on Paramagnetic Resonances, Research Lab. of Electronics, Massachusetts Institute of Technology, Cambridge, Mass., Feb 1960, pp 17–27.
[19] Goodwin, F. E., One-port and traveling-wave masers using coupled cavities, Research Rept 173, Hughes Research Labs., Malibu, Calif., Nov 1960.
[20] O'Meara, T. R., The coupled-cavity transmission maser—analysis, *IEEE Trans. on Microwave Theory and Techniques*, vol MTT-12, May 1964, pp 336–348.
[21] Goodwin, F. E., J. E. Kiefer, and G. E. Moss, The coupled-cavity transmission maser—engineering design, *ibid.*, pp 349–358.
[22] Nagy, A. W., and G. E. Friedman, Reflection cavity maser with large gain bandwidth, *Proc. IRE (Correspondence)*, vol 50, Dec. 1962, pp 2504–2505.
[23] Cook, J. J., L. G. Cross, M. E. Bair, and R. W. Terhune, A low-noise X-band radiometer using maser, *Proc. IRE*, vol 49, Apr 1961, pp 768–778.
[24] Kyhl, R. L., R. A. McFarlane, and M. W. P. Strandberg, Negative *L* and *C* in solid-state masers, *Proc. IRE*, vol 50, Jul 1962, pp 1608–1623.
[25] Sard, E. W., Tunnel (Esaki) diode amplifiers with unusually large bandwidths, *Proc. IRE (Correspondence)*, vol 48, Mar 1960, pp 357–358.
[26] ——, Gain-bandwidth performance of maximally flat negative-conductance amplifiers, *Proc. Symp. on Active Networks and Feedback Systems*, 1960, pp 319–344.
[27] Aron, R., Gain bandwidth relations in negative resistance amplifiers, *Proc. IRE (Correspondence)*, vol 49, Jan 1961, pp 355–356.
[28] ——, Bandwidth limitations and synthesis procedures for negative resistance and variable reactance amplifiers, Tech Rept 15, Electron Tube and Microwave Lab., California Inst. Tech., Pasadena, Calif., Aug 1960.
[29] Youla, D. C., and L. I. Smilen, Optimum negative resistance amplifiers, *Proc. Symp. on Active Networks and Feedback Systems*, 1960, pp 241–318.
[30] Getsinger, W. J., Prototypes for use in broadbanding reflection amplifiers, *IEEE Trans. on Microwave Theory and Techniques*, vol MTT-11, Nov 1963, pp 486–497.
[31] Aron, R., Bandwidth limitations and synthesis procedures for negative resistance and variable reactance amplifiers, Tech Rept 15, Electron Tube and Microwave Lab., California Inst. Tech., Pasadena, Calif., Aug 1960, pp 16–31.
[32] Riblet, H. J., Synthesis of narrow-band direct-coupled filters, *Proc. IRE*, vol 40, Oct 1952, pp 1219–1223.
[33] Cohn, S. B., Direct-coupled-resonator filters, *Proc. IRE*, vol 45, Feb 1957, pp 187–196.
[34] Pritchard, W. L., Quarter wave coupled wave-guide filters, *J. Appl. Phys.*, vol 18, Oct 1947, pp 862–872.
[35] Fano, R. M., and A. W. Lawson, Microwave filters using quarter-wave couplings, *Proc. IRE*, vol 35, Nov 1947, pp 1318–1323.
[36] Kyhl, R. L., Negative *L* and *C* in solid-state masers, *Proc. IRE (Correspondence)*, vol 48, Jun 1960, p 1157.