Masers for the *Telstar* Satellite Communications Experiment

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(Manuscript received January 28, 1963)

This paper discusses the design and characteristics of ruby traveling-wave masers operating at 4 gc. These masers, characterized by an average gain of ≈35 db over a bandwidth of 25 mc, are equipped with waveguide input transmission lines, rather than the previously employed coaxial cables. This change results in an over-all noise temperature of 3.5°K for these devices, rather than the 10°K exhibited by earlier masers. The maser noise temperature now closely approximates sky temperatures, which set the ultimate limit on earthbound receiver sensitivity. The improvements to be had by further reduction in amplifier noise are therefore almost negligible. A less well known maser property, i.e., its freedom from distortion, even when driven well into gain saturation, is discussed.

I. INTRODUCTION

In an active satellite communication system, the ultimate in ground station receiver performance is highly desirable, if not absolutely necessary. This follows directly from the limitations imposed by present rocketry on the payload, and thereby on the transmitter power, which can be placed in orbit. A major improvement in over-all system signal-to-noise ratio can be achieved much more easily and economically on the ground than in the satellite. Recognition of this fact led to the adoption of a giant horn-reflector antenna, and the selection of a ruby traveling-wave maser as a preamplifier in order to fully exploit this antenna's remarkable low-noise performance. The design considerations and performance of this maser are the subjects of this paper.

II. DESIGN OBJECTIVES AND THEIR SIGNIFICANCE

At the outset of the maser development program the following objectives and constraints were established:

(a) a minimum stable gain of 25 db

(b) an instantaneous bandwidth of 25 mc centered at 4170 mc

(c) lowest possible noise temperature

(d) an input impedance match better than or equal to 1.5:1 VSWR, and

(e) bath temperature of 4.2°K.

A minimum gain of 25 db is needed to render negligible the noise contribution of subsequent receiver stages. In the early receiver concept, the maser was to be followed by a low-noise traveling-wave tube. A typical value for the noise temperature of such a tube is 600°K. A maser with 25 db of gain would reduce the TWT noise contribution to the over-all system noise temperature to 1.9°K, a value which is small when compared to the initially projected total receiver noise temperature of approximately 50°K. Additional gain would reduce this even further, a point which will be pursued in a later paragraph.

The 25-mc instantaneous bandwidth requirement follows directly from consideration of the information transmission rate and wide index FM mode of transmission.

The demand for the lowest possible maser noise temperature is self-evident.

A good input impedance match is necessary in order to minimize delay distortion: i.e., the generation of weak reflected signals delayed in time with respect to the original. This could cause "ghosts" in TV transmission. In the Telstar system such distortion could arise through the following mechanism. A mismatch in the antenna-maser complex would reflect part of the incident signal, which would then be re-radiated. The radome, not being perfectly transparent, would in turn reflect a portion of this energy back to the receiver. Consideration of the path lengths and reflection coefficients in the entire system, together with the tolerable limits on delay distortion, led to the stipulation of maser input matching to a VSWR better than 1.5:1.

Operation at 4.2°K, rather than at some lower temperature where the gain and bandwidth requirements could be more easily satisfied, was dictated by the fact that this maser was intended to operate continuously over periods of several months. At 4.2°K, liquid helium is in equilibrium with its vapor at atmospheric pressure. If lower temperatures were required, the dewar would have to be maintained under a partial vacuum. This would mean periodic interruptions of service, since the dewar is opened to the atmosphere during each liquid helium transfer. Approximately two hours are needed to re-evacuate the dewar, thus lowering the temperature and restoring gain. For this reason, operation at 4.2°K was selected, and the attainment of the required gain-bandwidth product sought by means other than reduced temperature.

III. MASER DESIGN

3.1 *General Considerations*

The points of departure in maser design are the gain equation[1]

$$G = 27.3\ (-\chi'')(FfL/v_g) \tag{1}$$

where

G = electronic gain in db
χ'' = imaginary part of the ruby paramagnetic susceptibility
F = filling factor
f = frequency
L = maser physical length
v_g = group velocity of signal

and the gain-bandwidth relationship for the traveling-wave maser

$$B = \sqrt{\frac{3}{G-3}}\, B_m \tag{2}$$

where B is the 3-db bandwidth of the amplifier and B_m is the material linewidth (assuming a Lorentzian shape).

If slowing, S, is defined as $S = (c/v_g)$, where c is the free-space velocity of light, (1) can be rewritten in a form more easily interpreted for practical design

$$G = 27.3(-\chi'' F)\frac{1}{\lambda_0} SL, \tag{3}$$

where λ_0 = free-space signal wavelength. In this form, it is evident that increased gain can be achieved equally well by increasing either the slowing or the physical length of the maser. Since the maser requires a highly homogeneous transverse magnetic field, a very large magnet cross section is required. Therefore, a heavy penalty in weight is paid for gain achieved through increased maser length. This consideration led to the choice of a 5-inch maser length. The gain requirement has to be satisfied by maximizing the parameters χ'', F, and S. χ'' is a property of the active material and S is controlled by slow-wave structure design. F is partially determined by both.

The gain-bandwidth expression (2) in the case of a ruby (linewidth 60 mc) maser immediately leads to the conclusion that even for the minimum gain of 25 db, the obtainable bandwidth will be inadequate [taking an electronic gain of 30 db in order to allow for losses, the bandwidth would from (2) be 20 mc]. For this reason, the need for broad-banding techniques, to be discussed in later paragraphs, was evident in the earliest stages of design.

3.2 *Ruby*

Amplification in a maser is the result of the interaction of a microwave signal with a paramagnetic crystal in which a negative susceptibility, χ'', has been established through the inversion of the spin populations of two energy levels. In ruby at 4 gc, χ'' is maximized when the C axis of the crystal is aligned perpendicular to the applied dc magnetic field ($\theta = 90°$). The signal transition occurs between the lowest two energy levels $(-\frac{3}{2}, -\frac{1}{2})$, and pump power is applied between the outermost levels $(-\frac{3}{2}, +\frac{3}{2})$.[2]

The susceptibility of a ruby crystal in thermal equilibrium can be calculated as outlined in the Appendix. However, what is needed in order to evaluate the gain obtainable with a particular maser design is the "inverted" susceptibility: i.e., the susceptibility when the population distribution of spins between two energy levels has been inverted through the application of microwave pump power. No reliable method exists for calculating this susceptibility. An experiment, together with the calculated equilibrium susceptibility, will provide the required information. One can measure the ratio of the microwave gain obtained from a ruby crystal when pump power is applied to the microwave absorption when the crystal is in thermal equilibrium. This ratio is just that of the magnitudes of the inverted to equilibrium susceptibilities. Therefore, one obtains the inverted susceptibility by simply multiplying the calculated equilibrium value by this empirically determined number.

The magnitude of the inverted χ'' is strongly dependent upon the concentration of chromium in the ruby. At low concentrations, where there is essentially no interaction between neighboring Cr^{+++} ions, the inverted susceptibility is directly proportional to the concentration. As the concentration is increased, the Cr^{+++} ions interact more strongly with one another because of their greater proximity, and this interaction (cross-relaxation) renders pumping less efficient, reducing the inversion ratio and, thereby, the available gain. Typical behavior of the inverted susceptibility as a function of chromium concentration (measured at 5.6 gc and 4.2°K) is presented in Fig. 1. The concentration at which χ'' is a maximum occurs in the range 0.03–0.04 atomic per cent. Operating at a temperature of 4.2°K, the optimum inversion ratio obtainable at 4 gc has been found to be approximately 5.0. The corresponding calculated values for the inverted susceptibilities are

$$\chi_{xx}'' = -0.028,$$

$$\chi_{yy}'' = -0.0054,$$

and

$$\chi_{xy}'' = i\,0.012,$$

where the Z direction is taken parallel to the dc magnetic field and the X axis parallel to the C axis of the ruby.

Since the paramagnetic susceptibility is a tensor, the interaction of a microwave signal with the ruby is highly dependent upon the spatial coincidence of the crystal and RF fields of the proper polarization. This leads to the inclusion of the filling factor F in the gain equation. The term $\chi''F$ when expanded is

$$\chi''F = \frac{\int_m [\chi_{xx}'' \mid H_x \mid^2 + \chi_{yy}'' \mid H_y \mid^2 - \chi_{xy}''(H_x H_y^* - H_x^* H_y)]\, dv}{\int_s [\mid H_x \mid^2 + \mid H_y \mid^2]\, dv} \tag{4}$$

where

$$H_x = h_x' + ih_x''$$

$$H_y = h_y' + ih_y''$$

and where $h_{x,y}'$ is the amplitude of the RF magnetic field along the x,y axis of the ruby (see Fig. 2) and $ih_{x,y}''$ is the amplitude of the RF magnetic field that is 90° out of phase with $h_{x,y}'$. The subscript m on the in-

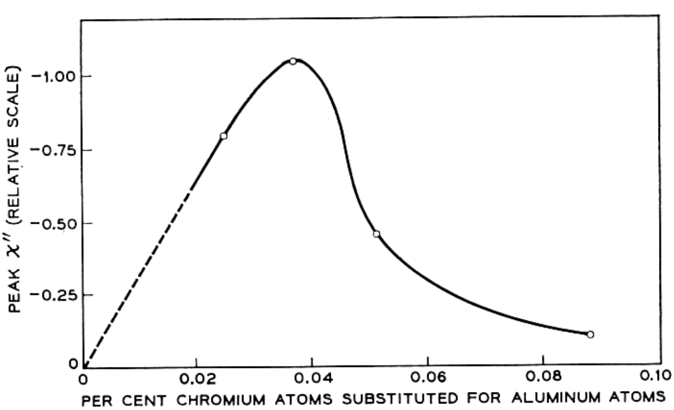

Fig. 1 — Inverted susceptibility vs concentration for ruby at 5.6 gc and 4.2°K.

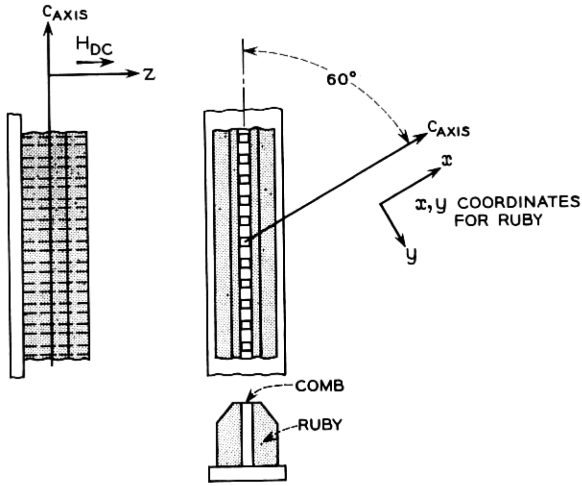

Fig. 2 — Orientation and coordinates for the ruby and comb structure.

tegral in the numerator means that the integral should be taken only over the volume occupied by the maser material, and the subscript s implies that the integral in the denominator should be taken over the entire volume of the structure. The term $|H_z|^2$ does not appear, since the fingers of the comb are resonating in a TEM mode and the Z direction is taken parallel to the fingers.

It is not possible to calculate the term $\chi''F$ with accuracy, since the configuration of the fields in the comb structure is only approximately known. An estimate can be made at the low-frequency edge of the traveling-wave structure passband where the RF magnetic field is approximately linearly polarized and parallel to the comb axis. At this frequency, $H_x = H \cos 60°$ and $H_y = H \sin 60°$ and, therefore, $\chi''F = -0.011$. This value for $\chi''F$, together with the 5-inch maser length, allows the evaluation of slowing required to achieve a given gain at 4 gc. Equation (1), with the insertion of the parameters

$$L = 5 \text{ inches}, \qquad f = 4 \text{ gc}, \qquad \chi''F = -0.011,$$

reduces to

$$G_{db} \approx 0.50\, S \text{ (from theory)}. \tag{5}$$

This calculated result led to the conclusion that it would not be difficult to design a maser with 40 db of net gain, since previous experience indicated that structures with slowings of 100 and losses of the order 10 db could be constructed.

It is possible to evaluate $\chi''F$ experimentally by building a trial structure of known slowing and measuring its electronic gain. This was done and a value of $\chi''F$, obtained from the gain equation (1), found to be -0.0076, i.e., 70 per cent of the theoretically derived value. This agreement, in view of the approximate knowledge of the RF fields in the comb structure, is surprisingly good. Equation (5) for a practical design should therefore read

$$G_{db} \approx 0.35\ S \text{ (experimental).} \tag{6}$$

The ruby used in these masers was purchased from the Linde Company in the form of standard 60° boules; i.e., the angle between the C axis and the rod axis was approximately 60°. The boules were selected for a chromium concentration of $\approx$0.035 atomic per cent by comparing the paramagnetic absorption of small samples cut from each boule with standard samples.

3.3 *Structure*

It is evident from (6) that a high slowing is required in order to provide adequate gain. A comb type structure, consisting of sixty-two 0.040-inch square fingers spaced 0.080 inch on centers, loaded on both sides with ruby, was employed (see Fig. 3). The transmission characteristics of such a comb not only are determined by the geometry of the metallic structure, but are strongly dependent upon the dielectric loading pro-

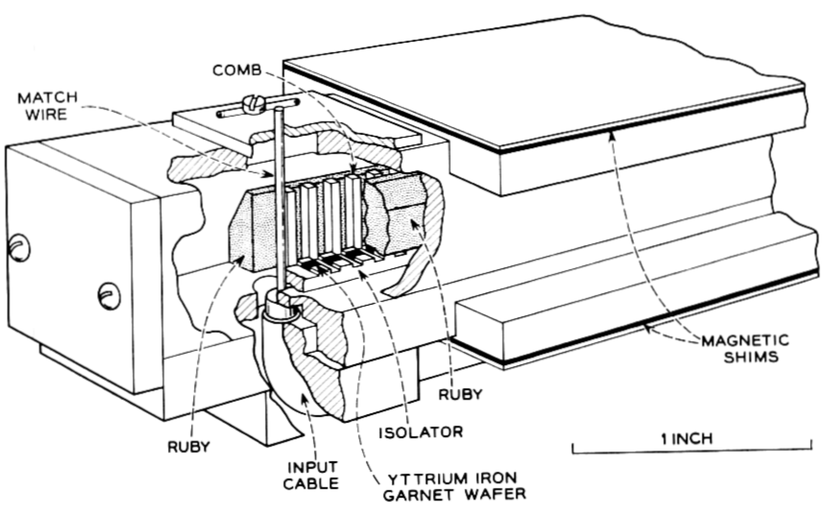

Fig. 3 — Cutaway view of structure.

vided by the ruby. Such a structure can be characterized by an ω-β response: i.e., the phase shift introduced per unit length (β) as a function of frequency (ω). The slowing is given by $c(d\beta/d\omega)$.

It is of advantage to use as much ruby as possible in such a structure, since by heavily loading with dielectric the structure size required for operation at a given frequency is reduced, thereby minimizing magnet weight. Further, the filling factor F is maximized.

When the cross section of the ruby loading is rectangular, the upper and lower cutoff frequencies of the loaded comb can be calculated. A variety of rectangular loadings was studied (see structures 1 and 2 of Fig. 4 and their ω-β diagrams), but it was found impossible to obtain sufficient slowing without the onset of "fold-over." "Fold-over" is the term applied to the occurrence of a double-valued ω-β diagram (curve 2 of Fig. 4). This phenomenon arises when the effective dielectric loading of the fingers of the comb is not a monotonic function of frequency. Knowledge of the field configuration within the structure is required

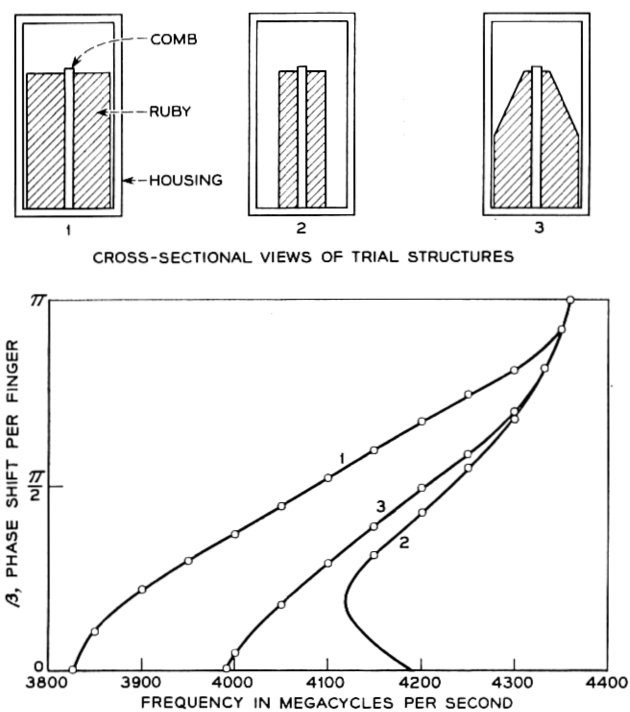

Fig. 4 — Bandpass characteristics for different types of dielectric loading.

for an understanding of this effect. At the lower cutoff frequency, the phase shift per unit length is zero, which implies that the electric field lines extend largely from the fingers to the side walls, as illustrated in Fig. 5. The effective loading is then a highly sensitive function of the gap between the ruby and wall. At the upper cutoff, there is a π phase shift per finger and the fields are concentrated in a region very near the fingers. The loading is then nearly independent of the ruby-to-wall gap. This can be summarized by the statement that the ruby-to-wall gap has a decreasing effect on the effective dielectric loading, and therefore the

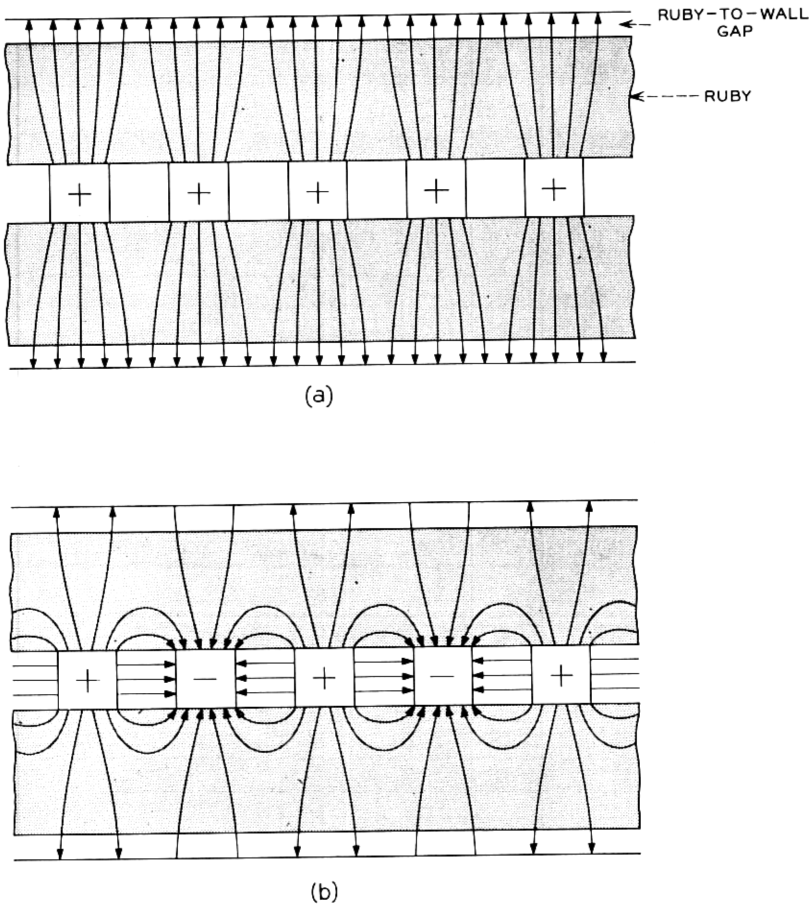

Fig. 5 — Field configuration in the comb structure: (a) zero phase shift condition at lower cutoff frequency; (b) π phase shift condition at upper cutoff frequency.

phase shift, as one traverses the passband from lower to upper cutoff. Increased slowing is achieved in a given structure by increasing the ruby-to-wall gap, thereby raising the lower cutoff frequency. If this process is carried too far, it is possible to reduce the effective loading at the lower cutoff to a value less than that present at a higher frequency. This results in the double-valued ω-β response. Maser operation under this condition is highly undesirable.[3] A "backward," as well as "forward" wave is supported. The sense of polarization associated with the "backward" wave is the reverse of that of the "forward" wave, and therefore the isolator (to be discussed) is rendered inoperative, leading to regeneration or oscillation. Therefore, other ruby geometries were tried in an attempt to account for the changing field configuration as a function of frequency and thereby obtain an effective loading which is monotonic. The cross section illustrated as structure 3 in Fig. 4 was selected as best. This gave the largest slowing ($S = 130$), with a single-valued ω-β characteristic. The slowing as a function of frequency is presented in Fig. 6.

With ruby symmetrically loaded on both sides of the comb as shown in Fig. 4, the maser will exhibit gain in either direction. Therefore, in order to prevent regeneration or oscillation, which would result from reflections due either to structure defects or imperfect input or output matches, an isolator must be incorporated within the structure. The amount of isolation provided should be sufficient for unconditional stability, so that the gain of the maser is not a function of the externally presented terminal impedances. The criterion for unconditional stability of a maser is that the round trip (input to output, back to input) loss must exceed the corresponding gain; i.e.

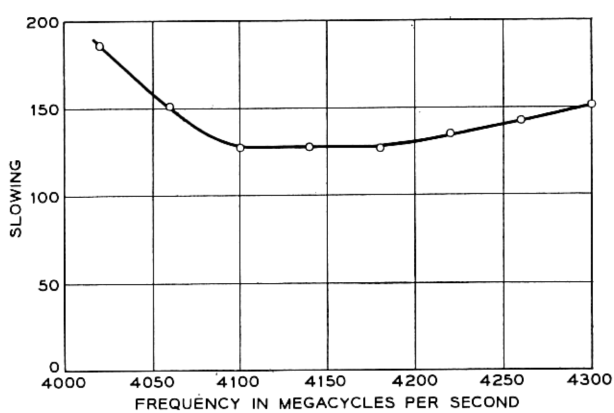

Fig. 6 — Slowing vs frequency for the masers at 4.2°K.

$$2(G_F - A_c) - A_{IF} - A_{IR} < 0 \tag{7}$$

where all quantities are expressed in db and

G_F = forward electronic gain (equal to reverse gain)
A_c = forward copper attenuation
A_{IF} = forward isolator attenuation
A_{IR} = reverse isolator attenuation.

The isolator employed is a linear array of 0.040-inch square polycrystalline yttrium iron garnet (YIG) wafers 0.004 inch thick, bonded, 0.080 inch on centers (see Fig. 3), to an alumina substrate. The aspect ratio of these wafers is so chosen that they are resonant at the signal frequency in the dc magnetic field required by the ruby. This array is placed on one side at the base of the comb and positioned to occupy that region of RF field most nearly circularly polarized (this optimizes the ratio of reverse to forward insertion loss). Typical performance of this iterated isolator is: reverse attenuation > 120 db; forward insertion loss approximately 4 db, at center band. The isolator forward loss rapidly rises on either side, since the slowing increases, thereby strengthening the interaction; and further, the circularity of the RF field polarization deteriorates. This behavior, as well as that of the copper losses, is illustrated in Fig. 7. With a slowing factor of 130, these masers should exhibit electronic gains of the order of 50 db and copper losses of approximately 2–4 db. Substitution of these numbers into (7) shows that the maser short-cir-

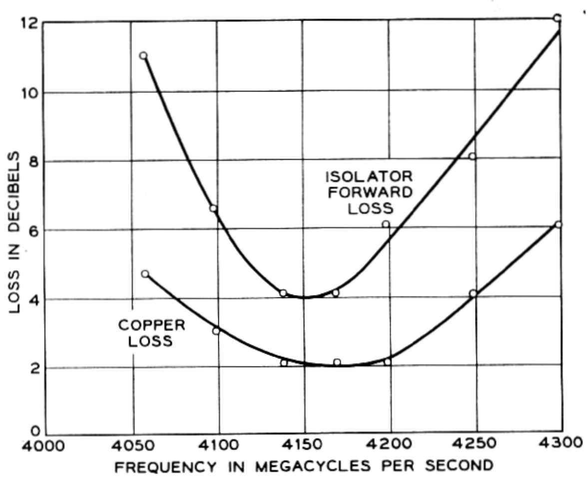

Fig. 7 — Typical losses for the structure at 4.2°K.

cuit stability margin should be greater than 30 db. In practice this is very desirable since it insures a smooth variation of the gain-frequency characteristic even in the presence of structural imperfections.

IV. MASER CHARACTERISTICS

4.1 *General*

In a uniform magnetic field the masers had net gains equal to or in excess of 42 db (corresponding to electronic gains $\geqq$ 47 db) and instantaneous 3-db bandwidths of approximately 16 mc centered at 4170 mc. These measured gains and bandwidths are in close agreement with those predicted by (5) and the bandwidth relationship. Since this was more gain and less bandwidth than required, it was necessary to correct this situation. Two distinct approaches were taken. The first of these was to exchange, within the maser, the excess center frequency gain for increased bandwidth by shaping the magnetic field along the length of the ruby, thereby broadening its effective linewidth. The second approach toward increasing the bandwidth was to consider the entire receiver as a whole, and to introduce equalization in the postamplifier. This latter course, which at first glance appears inefficient, actually leads to a larger effective gain-bandwidth product than broadening the ruby linewidth. This is illustrated in Fig. 8, which shows the ideal trade of center-frequency gain for effective bandwidth obtainable through the application of each technique. Both approaches were carried through experimentally, and will now be presented separately in the two following sections.

4.2 *Broad-Banding by Magnetic Field Shaping*

Since the resonant frequency of ruby is dependent upon the intensity of the dc magnetic field in which the crystal is immersed, its effective linewidth can be increased by making the field inhomogeneous over its volume. This was considered by Ostermayer[4] for several different variations of field along the maser length, and his results show that for a 25-mc bandwidth, the optimum exchange of gain for bandwidth is achieved if the magnetic field is made uniform for one-half the ruby length, and also uniform but of a different intensity over the remainder. A maser immersed in such a field is equivalent to two half-length masers in series tuned to different frequencies. It follows that for most effective inversion, two pump frequencies are required.

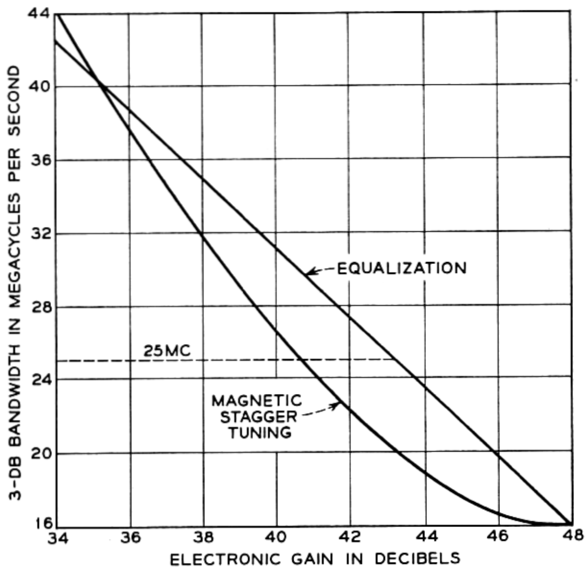

Fig. 8 — Trade of gain for bandwidth for a single-step stagger-tuned maser and for an equalized maser.

In practice it is not possible to achieve an abrupt step in magnetic field; there will be a finite transition region. In order to minimize this, the step in field was produced by inserting magnetic shims as close to the maser as possible, rather than by shaping the magnet pole pieces outside the dewar. The configuration of the shims used is illustrated in Fig. 3.

Using magnetic shims, the bandwidth was increased to 26 mc and the electronic gain reduced to 34 db, corresponding to a net gain of 28 db. Reference to Fig. 8 reveals that this loss in gain is 6 db greater than predicted by theory. There are two possible causes for this: first, a single-frequency pump was used; and second, the lateral homogeneity of the field may have been degraded by the shims, the width of which was severely limited by the dewar dimensions.

Fig. 9 is a plot of the electronic and net gain versus frequency over the tunable range of this maser. The electronic gain is nearly proportional to the slowing of the structure (Fig. 5); the small deviation (within 10 per cent) probably reflects slight changes with frequency of the filling factor. Fig. 10 is an oscillogram of instantaneous gain versus frequency. This maser was successfully employed at Holmdel, New Jersey, during the Telstar experiments.

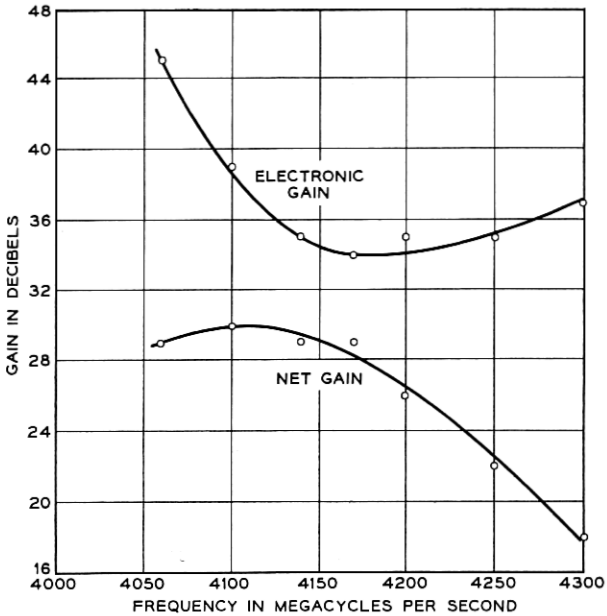

Fig. 9 — Gain of the stagger-tuned maser at 4.2°K.

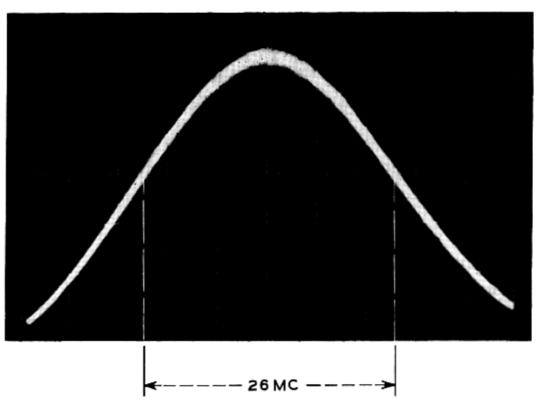

Fig. 10 — Oscillogram of instantaneous gain vs frequency for the stagger-tuned maser; the horizontal center line represents the 3-db point.

4.3 *Broad-Banding by Equalization of Amplifier following Maser*

In this approach, the maser is not modified, but rather the response of subsequent receiver stages is so equalized that the resultant over-all response has the required 25-mc bandwidth.

The gain-bandwidth relationship for equalization is simply generated by taking the electronic (not net) gain versus frequency characteristic of the maser, and finding the gain available at the appropriate deviation from center frequency as shown in Fig. 11. The shaded area then represents the excess gain to be absorbed by an equalizer. From Fig. 8, it is clear that the use of this technique would provide 2.5 db additional gain for a bandwidth of 25 mc beyond that ideally available by magnetic field shaping. Indeed, equalization is the more efficient method of increasing bandwidth up to approximately 40 mc. Magnetic field shaping should be employed for larger bandwidths. (The exact crossover is dependent upon both the detailed ruby line shape and the initial electronic gain.)

The theoretically ideal point for the insertion of an equalizer would be between the antenna and the maser input, for then the maser output would be flat over the band. Such an equalizer would have to be purely

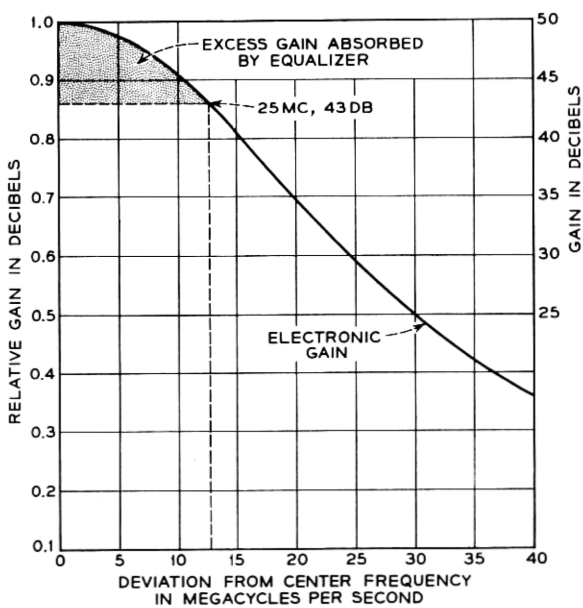

Fig. 11 — Determination of effective gain available with equalization.

reactive in nature in order not to seriously degrade the system noise temperature. The center band signal would have to be attenuated by approximately 7.5 db and this, if done resistively, would result in a noise temperature approaching 1500°K, which is clearly intolerable. A reactance in the input is, however, not acceptable in that it is incompatible with the requirement of a good input VSWR. For this reason, the equalizer was located after the maser in the receiver chain and took the form of a simple lumped RLC circuit at IF.

In going to IF equalization, one possible problem arises: maser gain saturation. The maser shows gain saturation; i.e., a monotonic decrease in gain when the signal level at its output exceeds -40 dbm. Since the center band gain of the unstaggered maser is 43 db, gain saturation will set in well below the level of the strongest signals to be encountered. This was investigated over the range of signal levels expected in the Telstar experiments (-90 to -70 dbm input). The results are presented in Fig. 12. When the input was increased from -90 to -70 dbm the gain of the maser decreased by 5 db, resulting in a signal level increase at the mixer of 15 db. This gain reduction will raise the system noise temperature somewhat, but since the gain reduction is present only when the signal level is high, the slight increase in system noise temperature is of no consequence. In this sense, the maser gain saturation does nothing more than to provide weak limiting action.

A second-order effect noted was a change in the shape of the gain-frequency characteristic arising from the fact that signals at the center frequency drive the amplifier further into saturation than do signals at the band edges. The maximum change was a 3-db reduction in center frequency gain compared to the band edge gain, as illustrated in Fig. 12. These measurements were made on a CW single-frequency basis, and could easily overemphasize, by an order of magnitude, the effect which would be found in an FM system. This effect would cause difficulty in designing a proper equalizer since exact compensation could be accomplished at only one signal level. However, it was decided that if the equalizer were so adjusted as to provide a low signal gain characteristic with a 1.5-db peak at center frequency relative to the band edge, then at high level, the response would at worst show a 1.5-db dip. This behavior would meet the normal 3-db bandwidth specification, and therefore this change in response with signal level was considered acceptable.

An additional factor to be considered when a maser is operated in the gain saturation regime is distortion. In conventional amplifiers, such as the electron tube, gain saturation and distortion are closely related, and formulae exist for the calculation of the distortion products from gain

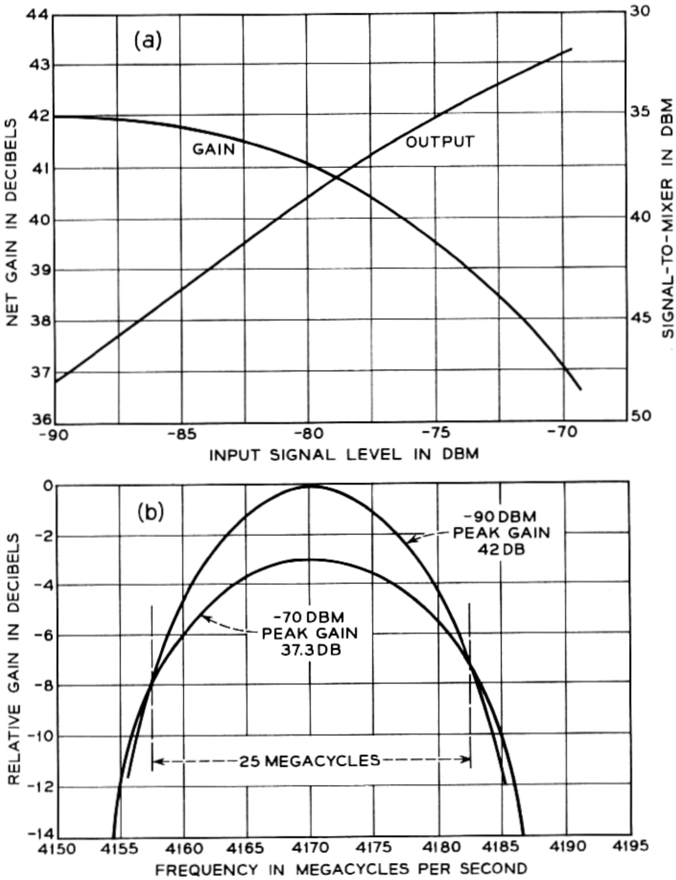

Fig. 12 — Maser signal saturation characteristics: (a) maser gain saturation; (b) maser response as a function of input level.

saturation curves. The behavior of a maser is, however, very different. This can be seen by considering the basic amplification process, stimulated emission.

The probability that photons will be added to the exciting RF field in a maser is given by the expression

$$W_{12} = K \mid \mu \mid^2 (N_2 - N_1) H_{rf}^{\ 2} \tag{8}$$

where

K is a collection of physical constants,

$\mid \mu \mid^2$ is the matrix element of the transition, a measure of the intrinsic probability of the transition occurring, which to first-order approximation, (i.e., low RF fields), is a constant.

$(N_2 - N_1)$ is the difference in the spin population of the two levels under consideration,

and

H_{rf}^2 is a measure of the power level of the stimulating radiation.

The population difference $(N_2 - N_1)$ is a function of the signal power level at which a maser is operated, decreasing monotonically as the level is raised. At any fixed average power level it is a constant, since a time constant which is very long compared to the period of the carrier frequency is associated with it. The value of this time constant is different for each of two cases: a sudden increase in signal level or a sudden decrease in level. A calculation based on the reduction of the energy stored in the inverted spin system shows that for a typical ruby maser the time required for the gain to reach a new equilibrium after the input signal has been raised from zero to −70 dbm is approximately 1 second. The time characteristic of gain recovery, when the signal level is reduced, is approximately 0.1 second, as governed by the spin lattice relaxation times. Gain changes are therefore very slow at signal levels consistent with the use of a maser as a low-noise preamplifier. The distortion arising from these gain changes is therefore no more serious than that introduced by an AGC system.

Higher-order solutions for the matrix element $|\mu|^2$ do exhibit a dependence upon H_{rf}^2, and therefore a source of distortion exists. A theoretical analysis and experiments[5] both show that, at signal levels normally found in a low-noise maser preamplifier, the power in distortion products lying within the significant frequency range is well below the noise generated by the maser itself. For example, if two signals at frequencies f_1 and f_2 simultaneously emerge from a maser at a level of −30 dbm, the third-order intermodulation products, $2f_1 - f_2$ and $2f_2 - f_1$, will be found at a level of −185 dbm,[5] which is approximately 95 db below the output noise of a 4°K, 25-mc maser.

For the reasons presented, the maser is, from the system engineering point of view, a completely distortion-free amplifier.

The use of this combination of an unstaggered maser and IF equalizer provided an effective net gain of 34.5 db at the band edges. This gain was sufficient to allow feeding a mixer directly from the maser output without degradation of the receiver noise temperature. The mixer had a noise temperature of approximately 4300°K which, reflected back to the maser input through 34.5 db of gain, appears as 1.5°K.

Equalized receivers were employed at Andover, Maine, and Pleumeur-

Bodou, France, and will be provided for the German installation. The performance obtained was satisfactory in every respect.

V. MASER TERMINALS AND AUXILIARY STRUCTURE

In all previous masers, the largest contributor to the noise temperature has been the loss in the input transmission line. These, in the past, have been constructed of thin wall, stainless-steel coaxial cables in order to minimize heat conduction from their room temperature access to 4.2°K. A thin copper plating was employed to minimize electrical losses. (A delicate balance between electrical and thermal conductivity is required.) Masers using coaxial cables have had typical over-all noise temperatures of 10°K, of which only 2°K was inherent in the masers themselves. Waveguide, which intrinsically has lower loss than coaxial cable, was used for the input lead of the Telstar masers in an effort to obtain the lowest possible noise temperature. This waveguide was constructed of 0.020-inch thick seamless stainless steel and internally plated with 0.0002 inch of copper. The room temperature loss of such guide is approximately 0.1 db in the lengths required. The waveguides used in the final assemblies were selected for low-noise performance from many which had been initially prepared. This was accomplished by connecting the various waveguides, shorted at the far end, to an operating maser and noting the maser noise output.[6]

The waveguide extends from room temperature to well below the normal liquid helium level in the dewar. A transition to 0.140-inch diameter solid coaxial cable is employed (Fig. 13) and the center conductor of this cable is extended into the maser proper where it forms the final match to the comb structure (Fig. 3). Coaxial cable is permissible below the helium level, since the noise contributed by a given loss at 4.2°K is a factor of 70 less than would arise if the same loss were present at room temperature. The success of the arrangement can be judged by the measured noise temperature of these masers, approximately 3.5°K.

A new technique was employed to measure the noise temperature of these masers. The ratio of the noise power output of the maser with a matched load connected to its input to the noise power output with a short circuit at the input was determined. Since noise power is directly proportional to noise temperature, these quantities can be interchanged, provided one is consistent.

When a matched load is connected to the input of a maser whose input loss is small, the noise temperature observed at the output will be:

$$(T_{\text{out}})_1 = G(T_L + T_I + T_{\text{MF}}) \tag{9}$$

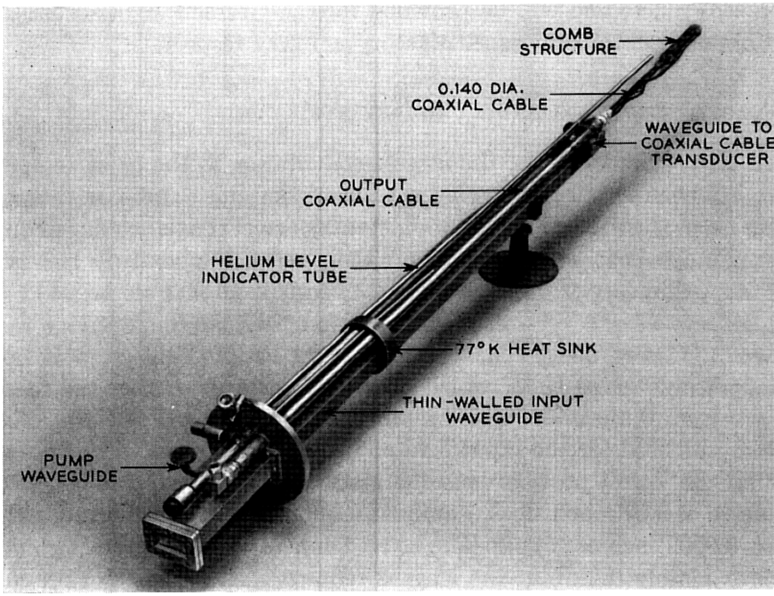

Fig. 13 — Maser head.

and when a short circuit is connected to the input, the output noise temperature is:

$$(T_{\text{out}})_2 = G(2T_I + T_S + T_{\text{MF}} + T_{\text{MR}}) \tag{10}$$

where

- G = power gain of the maser
- T_I = noise temperature due to losses in the input
- T_{MF} = noise temperature of the maser in the forward direction
- T_{MR} = temperature of the noise power emitted by the maser in the reverse direction
- T_L = temperature of the matched load, and
- T_S = noise temperature due to losses in the movable short.

The origin of (9) is clear, the noise contributed by the load and input losses being directly additive with forward-traveling maser noise. When the short is in position, the noise power generated by the input lead traveling away from the maser, as well as the noise power emitted in the reverse direction by the maser itself, are reflected, rather than absorbed, and therefore also contribute to the noise observed in the maser output. For this reason, the input noise appears doubly weighted, and the maser reverse noise enters in (10). An observable quantity is the ratio of (9) to (10), i.e.

$$\frac{(T_{\text{out}})_1}{(T_{\text{out}})_2} = \frac{T_L + T_I + T_{\text{MF}}}{2T_I + T_S + T_{\text{MF}} + T_{\text{MR}}}. \tag{11}$$

The noise temperature of the maser, referred to the input terminals, is equal to $T_I + T_{\text{MF}}$. T_L is just equal to room temperature, approximately 300°K. T_{MF} and T_{MR} can be calculated from the theory of the traveling-wave maser and are typically 1.5°K and 6.5°K, respectively.

The one remaining parameter to be evaluated in (11) is T_S. This can be determined by any one of a number of standard techniques, and is typically found to be of the order of 1°K. Therefore, T_I can be calculated from the ratio and the maser noise temperature determined.

If the situation were as ideal as has been presented, the measurement of maser noise temperature would be well in hand. However, in practice the ratio of the maser noise outputs is found to vary as the position of the short circuit is changed. This is due to noise coherence effects which occur because of a limited bandwidth detection system and to small mismatches in the system. A detailed analysis of these effects by W. J. Tabor, which will be published separately, shows that the correct value for the noise temperature can be calculated, if one substitutes the average value of the ratio of observed noise powers into (11). This technique, which employs standard microwave components, i.e., a matched termination and a movable short in contrast to refrigerated loads, is capable of good accuracy. The range of uncertainty in the measurement of these masers was ±0.5°K.

The maser output is coaxial, since the noise contribution due to loss following the maser gain is negligible. The pump line is thin-walled WR28 waveguide. Fig. 13 is a photograph of the maser "head" which illustrates the various connections.

Fig. 14 shows the entire assembly except for the microwave pump source. The dc magnetic field is supplied by a 450-pound Alnico magnet, which allows the tuning of the maser over the entire structure passband by means of movable iron shunts. The dewar is of the standard type for liquid helium except for one innovation. A 77° heat station, in the form of a copper ring thermally tied to the liquid nitrogen jacket, was incorporated 10 inches below the room temperature flange (top). Its purpose is twofold: to reduce the thermal gradient to the liquid helium along the maser head, and to reduce the waveguide temperature in as short a length as possible in order to minimize thermal noise generation. With one filling of liquid helium (10 liters) the maser could be kept in opera-

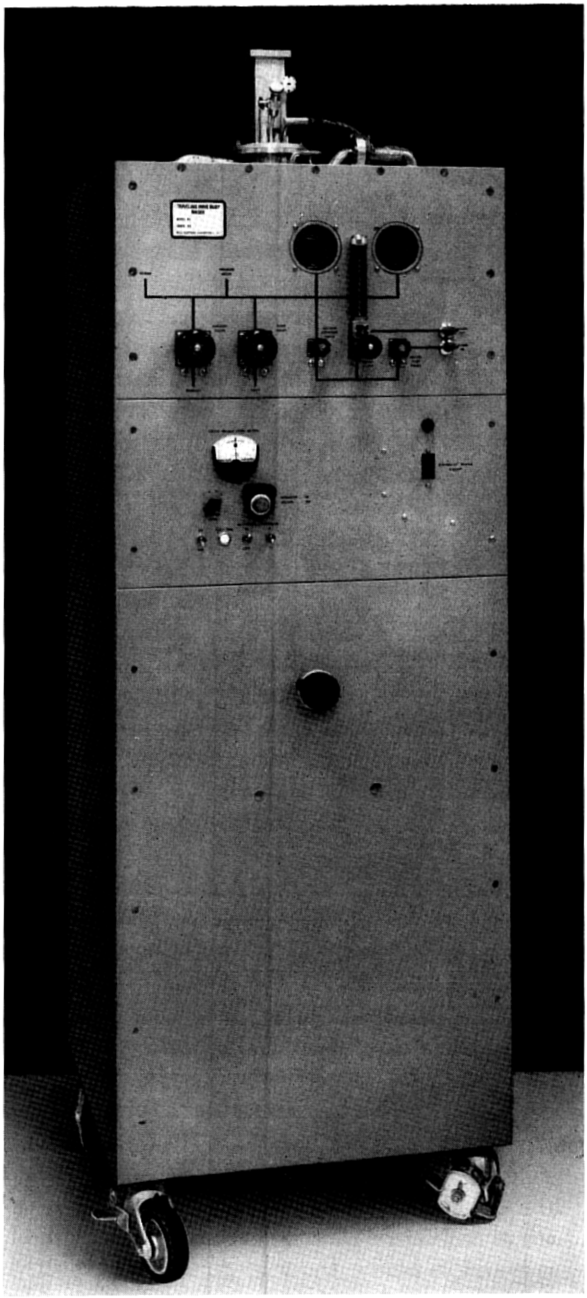

Fig. 14 — Complete maser package.

tion for approximately 20 hours. Refilling could be accomplished without disturbing maser performance.

VI. SUMMARY

The performance of the masers is given by the following data:

Center frequency:	4170 mc
Effective instantaneous bandwidth:	25 mc
Effective gain:	Approx. 34.5 db (equalized receiver) 28 db (magnetically staggered)
Pump frequency:	30,175 mc
Pump power:	70 mw
Magnetic field:	Approx. 3300 gauss
Over-all noise temperature:	3.5°K
Bath temperature:	4.2°K
Liquid helium consumption:	Approx. $\frac{1}{2}$ liter/hr
Helium capacity:	10 liters
Power output at 1-db gain compression:	−38 dbm.

The effective noise temperature, 3.5°K, of these amplifiers is almost a factor of 3 less than previously attained. Indeed, it is so low as to closely approximate the minimum noise temperature of the atmosphere itself. It therefore appears that the ultimate useful amplifier sensitivity has been achieved for application in terrestrial receivers.

VII. ACKNOWLEDGMENTS

The authors wish to acknowledge the role played by H. E. D. Scovil in the development of these masers. The importance of his insight and continued guidance cannot be overemphasized.

We are indebted to E. O. Schulz-DuBois and E. D. Reed for reading this manuscript and making valuable suggestions. We would like to thank P. J. Pantano for his valuable assistance in the mechanical design and microwave measurements; his enthusiastic efforts in the early stages of this program were invaluable.

The authors also wish to show appreciation to certain members of the group for access to unpublished data: namely, S. Harris and R. W. DeGrasse, for calculations involving the comb bandpass cutoff, and to F. W. Ostermayer for design equations used in broadbanding.

APPENDIX

Formulas for the Calculation of χ''

The tensor components of the susceptibility can be calculated from the following formulas

$$\chi_{xx}'' = \frac{\pi g^2 \beta^2}{\mu_0 h} g(f - f_0)(\rho_{-\frac{3}{2}} - \rho_{-\frac{1}{2}}) \mid \langle -\tfrac{1}{2} \mid S_x \mid -\tfrac{3}{2} \rangle \mid^2 \quad (12)$$

$$\chi_{xy}'' = \frac{\pi g^2 \beta^2}{\mu_0 h} g(f - f_0)(\rho_{-\frac{3}{2}} - \rho_{-\frac{1}{2}}) \langle -\tfrac{1}{2} \mid S_x \mid -\tfrac{3}{2} \rangle \langle -\tfrac{1}{2} \mid S_y \mid -\tfrac{3}{2} \rangle \quad (13)$$

etc., where μ_0 is the permeability of free space, h is Planck's constant, g is the spectroscopic splitting factor, β is the Bohr electronic magneton, ρ_i is the density of spins in the energy level i, and $g(f - f_0)$ is a normalized line shape function; i.e.,

$$\int g(f - f_0)\, df = 1.$$

All the units are expressed in mks units. If emu units are used, μ_0 must be replaced by $1/4\pi$.

In the case of ruby for operation at $\theta = 90°$, the transition probability between levels $-\frac{1}{2}$, $-\frac{3}{2}$ contain only S_x and S_y terms with $S_z = 0$, where the Z direction is parallel to the dc magnetic field and the X axis is parallel to the C axis of the ruby. Therefore, the susceptibility tensor for this case consists only of terms χ_{xx}'', χ_{xy}'' and χ_{yy}''. The values of the matrix elements can be computed from the data given by Schulz-DuBois.[7]

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