PROJECT ECHO

The Dual Channel 2390-mc Traveling-Wave Maser

By R. W. DE GRASSE, J. J. KOSTELNICK, and H. E. D. SCOVIL

(Manuscript received April 26, 1961)

Reflected 2390-mc signals from the Echo I satellite were received by a horn-reflector antenna and amplified by solid state traveling-wave masers. This paper describes the design of the dual channel maser amplifiers for this experiment. Each maser has sufficient gain (>33 db) to override the noise of the following stage. Unconditional stability is obtained by the use of distributed ferrimagnetic isolator elements. Their instantaneous bandwidth is 13 mc, centered at 2390 mc. The effective input noise temperature is 8°K.*

I. INTRODUCTION

This paper discusses the design of an S-band traveling-wave maser for the Project Echo satellite communication experiment.[1] The masers described here were used at Bell Telephone Laboratories, Holmdel, New Jersey, receiving terminal to amplify the 2390-mc signals reflected from the passive Echo I satellite and received by the 20-foot horn-reflector antenna.[2]

The 2390-mc signal was transmitted with circular polarization. Imperfections in the transmission path such as a not perfectly spherical satellite could lead to deviations from the originally circular polarization. Such effects would show up in terms of a signal having the opposite sense of circular polarization. A quarter-wave plate in the antenna feed converted both senses of circular into orthogonal senses of linear polarization, which were then fed separately to the inputs of two masers. Thus one maser received the polarization as transmitted and served as pre-

* Although this equipment was designed by the Bell System as part of its research and development program, it was operated in connection with Project Echo under Contract NASW-110 for the National Aeronautics and Space Administration.

amplifier for the signal channel. The other maser served as a preamplifier for a monitoring channel which received data on the imperfections of the transmission path.

The system used frequency modulation. It required a receiving bandwidth of approximately 1 mc centered at 2390 mc for the signal. A slightly wider bandwidth was required, however, since continuous sky-noise monitoring was desired at 2388 mc; this frequency was outside but close to the signal channel. Further receiving system details are given in the accompanying paper by Ohm.[3]

II. SIGNAL REQUIREMENTS

The system objective called for masers with the following requirements:

1. two identical amplifiers for duplex operation;
2. lowest possible noise temperature;
3. bandwidth greater than 3 mc;
4. long-term gain stability;
5. at least 33 db gain;
6. dynamic range greater than 60 db;
7. sufficient running time between helium transfers to permit operation for a full sequence of neighboring satellite passes;
8. center frequency 2390 mc.

Because of items 2, 4, and 6, it was decided that traveling-wave masers would be the most desirable. It was shown previously[4] that these general objectives could be met at 6 kmc. Apart from the frequency, the main differences were the requirement for a higher gain and no electronic tuning. This suggested the use of the 6-kmc traveling-wave maser as a basis for design, the main departure being a much narrower-bandwidth slow-wave structure with greater slowing.

Item 7 suggested a batch helium system using a stainless steel dewar with sufficient liquid storage capacity to give the required running time.

The two amplifiers were located in the same dewar and magnetic field, in order to obtain duplex operation.

III. THE ACTIVE MATERIAL (RUBY)

Chromium-doped aluminum oxide (ruby) was the one material which was proved to have the requisite properties. Fortunately, essentially complete information was available on the maser properties of this material at 2390 mc from the work of Geusic.[5] In particular it was known that 0.05 per cent chromium was optimum and that the $\theta = 90°$, high-field, single-pump operation was best.

The value of $\chi''_{\pm}$ for circular polarization is given by Equation (12) of Ref. 4. Geusic obtained the inverted state densities $(\bar{\rho}_n - \bar{\rho}_{n'})$ directly from a measurement of the inversion ratio, $\chi''_{\text{pump on}}/\chi''_{\text{pump off}}$. From the inversion ratio of 3.6 at 4.2°K he computed $-\chi_+''$ and $-\chi_-''$, the inverted susceptibilities, for the two senses of circular polarization defined with respect to the applied dc magnetic field. He gives $\chi_+'' = -0.018$ and $\chi_-'' = -0.0021$ when the material is pumped to saturation, the principal axis of the susceptibility tensor being along the C-axis of the crystal.

IV. THE INTERACTION BETWEEN THE ACTIVE MATERIAL AND THE SLOW-WAVE STRUCTURE

The gain in a length of structure, l, is given by Equation (5) of Ref. 4 as

$$G = e^{-\chi''_{\max} F(\omega v_g) l},$$

where $\chi''_{\max}$ is the magnitude of the diagonalized χ'' tensor, and the filling factor, F, is defined by

$$F = \frac{\int H \cdot \chi'' \cdot H^* \, ds}{\chi''_{\max} \int H^2 \, ds}.$$

Since $\chi''_{\max}$ is a property of the material and may be computed from Geusic's values for $\chi''_{\pm}$, we find $\chi''_{\max} = 1.4\ \chi''_+$. In order to obtain the largest gain, one should maximize F. This would occur if the structure were completely filled with ruby and if the RF fields everywhere had the correct ellipticity. In practice, however, this cannot be done. The comb structure cannot be conveniently filled with active material between the fingers, and some air dielectric has to be left near the tips in order to control the frequency and bandwidth. Further, the RF field configuration is controlled by the structure, and the ellipticity is different in different regions. In principle, the C-axis of the crystal can be oriented to give the best value for F. Unfortunately, at the time this device was built, large boules could not be obtained with the optimum orientation. It was necessary, therefore, to use the C-axis at 60° to the axis of the comb.

The 6-kmc maser was loaded with ruby on only one side, and the ratio of the db gains in the opposite directions of propagation was 3.5. A ratio of about 2 was expected at 2.4 kmc, because of the increased ellipticity of the susceptibility tensor. It was decided, therefore, that a design would be attempted in which both sides of the slow-wave structure would be loaded with ruby in order to obtain maximum gain. In obtaining this increase in gain, we paid the penalty of reciprocal electronic gain. This led to a rather difficult job for the isolator, since short-circuit stability required the isolator reverse loss to now exceed twice the ruby gain.

The RF magnetic field patterns of the comb are not known exactly; nevertheless it was possible to make a reasonable estimate of the product $\chi''_{\max}F$, and hence obtain the magnetic Q_m at 4.2°K. This approximate computation gave

$$Q_m = \frac{1}{\chi''_{\max}F} \approx 190.$$

The electronic gain may be rewritten [Equation (22) of Ref. 4] as

$$G = 27.3\left(\frac{SN}{Q_m}\right),$$

where S is the slowing factor and N the number of free space wavelengths in the length of the structure. Assuming an amplifier length of 5 inches and a $Q_m = 190$,

$$G \approx 1.4(10^{-1}S).$$

If the structure and isolator forward loss is assumed to be about 12 db, we see that a slowing factor of about 340 is required for operation at 4.2°K. As this was considered somewhat excessive, it was decided to operate at a pumped helium temperature of about 1.6°K. At this temperature cross-relaxation reduces the inversion ratio to about 2.5. Taking this into account, we obtain a required slowing of 190.

It is now possible to estimate the number of sections required in the slow-wave structure and the structure bandwidth from Equation (38) of Ref. 4,

$$SN = N_s \frac{f_0}{2\pi}\frac{d\varphi}{df},$$

where f_0 is the frequency at which the circuit fingers have an electrical length of one-quarter wavelength, N_s is the total number of sections in the structure, and $d\varphi/df$ is the rate of change of phase shift per section with frequency. Using an empirical relationship between structure bandwidth B_s and $d\varphi/df$, which is

$$\frac{d\varphi}{df} \approx \frac{k\pi}{B_s},$$

where $k \sim 0.6$, then

$$SN = 0.3N_s \frac{f_0}{B_s},$$

and putting in values we obtain

$$\frac{B_s}{N_s} \approx 3.8,$$

where B_s is in megacycles. In the final design, 25 sections were used, which indicates an approximate structure bandwidth of 95 mc, i.e., about 4 per cent. Previous experience showed that fabrication difficulties were often encountered with smaller percentage bandwidths.

V. THE SLOW-WAVE STRUCTURE

One difficulty with the use of the comb structure at low frequencies is the increase in size if the structure is simply scaled in dimensions. The nominal finger length is $\lambda/4$. This dimension is along the direction of the applied dc magnetic field; consequently, it will be a determining factor in the magnet gap size. The actual finger length required can be reduced by capacitive loading at the finger tips and by utilizing the dielectric constant of the ruby maser material.

The 6-kmc traveling-wave maser employed a finger length of 0.87 $\lambda/4$. In order to keep the magnet size down, the Echo maser was designed to use a length of 0.64 $\lambda/4$. The outer walls of the comb structure, which form the pump frequency waveguide, are 0.400 by 0.850 inches, which is close to X-band waveguide inside dimension. These dimensions give a 0.050-inch gap between the finger tips and the waveguide wall and increase the fringe capacity considerably. The final structure employed an array of 25 fingers having a diameter of 0.070 inch and a pitch of 0.214 inch. The unloaded phase shift per section, φ, versus frequency, f, curve for this structure is shown in Fig. 1 as curve A. The effects of dielectric loading are illustrated by curves B and C. The length of the loading along the fingers determines, to a good approximation, the upper cutoff frequency of the structure. The position of the lower cutoff frequency is then determined by the height of the loading perpendicular to the fingers. Full-height loading, without essentially changing the bandwidth, as in B, lowers the pass band.

In order to obtain maximum gain, full-height loading of the ruby is indicated near the base of the fingers where the RF magnetic fields are strongest. Consequently, the final amplifier design was based on the loading shown in Fig. 1. Under this condition the lower cutoff is deter-

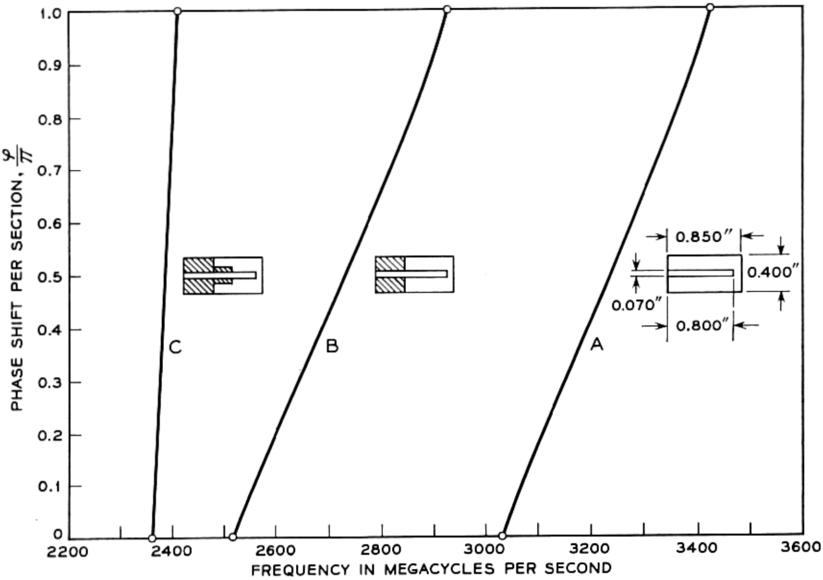

Fig. 1 — Unloaded phase shift per section vs. frequency.

mined primarily by the length of the full-height ruby loading, and is little effected by the partial-height loading. The high-frequency cutoff is determined primarily by the length of ruby directly in contact with the fingers.

VI. THE ISOLATOR

Development of a satisfactory isolator was essential to the design, since the ruby gain was reciprocal. An important aspect of the isolator design was the adjustment of geometry in order to obtain ferrimagnetic resonance at the ruby paramagnetic resonance field. A geometry approaching a thin disk was required, and polycrystalline iron garnet disks with an aspect ratio of 8:1 were used.

Isolator tests were carried out in a crossed-wire strip-line structure in order to determine the performance of the material. Ref. 6 shows typical curves.

The actual volume of yttrium iron garnet which could be used to obtain sufficient reverse loss was determined by the aspect ratio and the physical limitations imposed by the structure dimensions. The remaining parameter was the location of the disks in the signal RF magnetic field. The high field near the base called for placement of the disks in a plane near the base; they were, however, spaced a small distance away to avoid interaction with the wall and simplify fabrication. The disks were located equidistant between fingers because the RF fields are most circular in this region. Finally, a compromise was made between high reverse loss and high reverse-to-forward loss ratio in choosing the transverse position of the disks between the fingers and the waveguide wall. The isolator has a reverse loss >120 db and a forward loss of ~ 10 db.

VII. THE AMPLIFIER PACKAGE

The final maser cross section is shown in Fig. 2 along with the method used to hold the isolator disks, which are mounted in a composite alumina sandwich. An equivalent piece of alumina is used on the other side of the comb to symmetrize the loading. Details of the coaxial-to-comb matching arrangement are shown in Fig. 3. By using successive adjustment of the spacing, d, the bend in the wire, and the adjustable short, an adequate match could be obtained.

The dual maser package is shown in Fig. 4. The signal input and output coaxials were connected to low-heat-conductivity air-dielectric coaxial cables. The input cables have a diameter of 0.750 inch and an impedance of 70 ohms. Low electrical loss is important in these cables, since they have a higher noise contribution than any other single part of the amplifier. The output cables are 0.50 inch in diameter with a 50-ohm impedance. The pump frequency waveguide is Ku-band, and a 3-db top-wall short-slot coupler is provided to divide the incoming pump power equally for the two maser amplifiers.

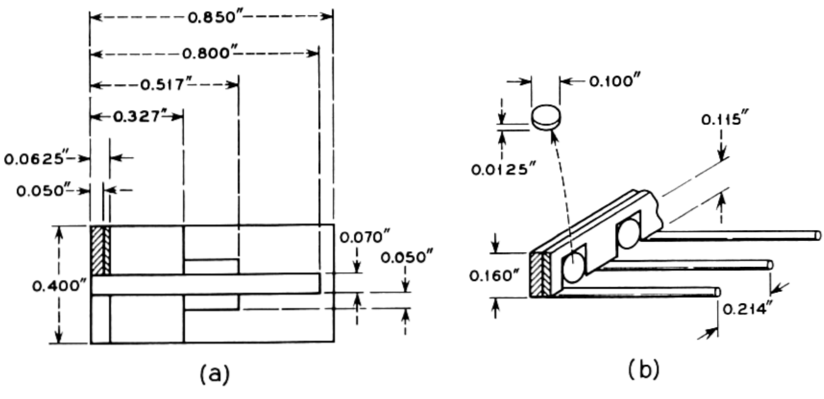

Fig. 2 — (a) Maser cross section including isolator; (b) placement of garnet disks relative to comb structure.

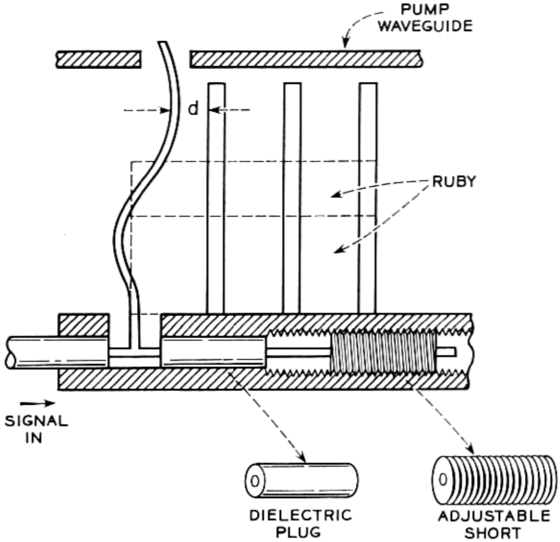

Fig. 3 — Coaxial-to-comb matching arrangement.

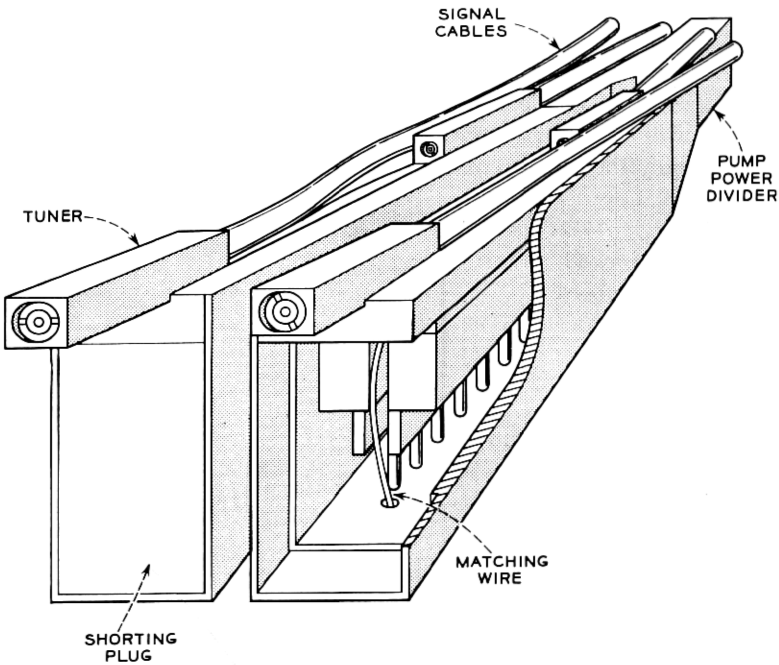

Fig. 4 — Two-maser package.

The cable assembly and traveling-wave maser structure are located in a stainless steel dewar with a 10-liter helium capacity. The tip of the dewar is between the poles of a permanent magnet whose field can be adjusted with movable shunts. The dewar and magnet are mounted in a frame which also contains the microwave pump klystron, the automatic frequency control discriminator and associated waveguide, the automatic nitrogen transfer controls, temperature and level monitoring meters, and the vacuum control valves and gauges.

The entire assembly is mounted just beneath the antenna feed in the cab at the back of the antenna, which also houses the remainder of the microwave receiver and the monitoring and calibration equipment. The vacuum pump is remotely located at the base of the antenna.

The dual maser amplifier characteristics are as follows:

Center frequency:	2390 mc
Instantaneous bandwidth:	13 mc
Tuning range:	±10 mc
Gain, channel I:	36 db
Gain, channel II:	33 db
Pump frequency:	13 kmc
Pump power:	70 mw per channel
Magnetic field:	2530 oersteds
Noise temperature:	8 ± 1°K
Operating temperature:	1.8°K
Running time:	20 hours (approximately)
Helium capacity:	10 liters

The noise temperature is somewhat greater than the expected 5°K. This is believed due to excess loss in the input cables and mismatch, which together seem to contribute approximately 7°K, the maser proper contributing about 1°K. Using standard laboratory transfer procedures, about 12 liters of helium are needed to fill the dewar.

VIII. ACKNOWLEDGMENTS

We are indebted to P. P. Cioffi and D. C. Hogg, who supplied the variable shunt permanent magnet and stabilized pumping klystron respectively. We wish to thank J. E. Geusic and E. O. Schulz-DuBois for making measurements on the ruby and the isolator material, as well as for their many useful suggestions. We acknowledge the help of D. Halvorsen in the mechanical design.

The device was installed in the antenna in collaboration with E. A.

Ohm, who was responsible for the cryogenic transfer system used in the field.

The use of this device in Project Echo was in connection with National Aeronautics and Space Administration Contract NASW-110.

APPENDIX

Some Remarks on a Double-Valued $\omega\beta$ Diagram

At one stage of the design considerable difficulty was experienced when the device persisted in being unstable. These oscillations were quite unexpected, since they occurred well within the passband of the amplifier and at a frequency where the isolator seemed to give excellent reverse loss. It had also been observed that the passband with the isolator magnetic field at resonance was much narrower than when it was off resonance, and that sometimes a minimum in transmission would appear in the passband. It is now believed that these effects can be explained by an anomolous mode of propagation.

As previously mentioned, the height of the loading primarily controls the lower cutoff, while the width primarily controls the upper cutoff. By the use of a small-height dielectric loading, the upper cutoff of the empty structure can be shifted below the lower cutoff. Under these conditions the structure is backward wave; i.e., the phase and group

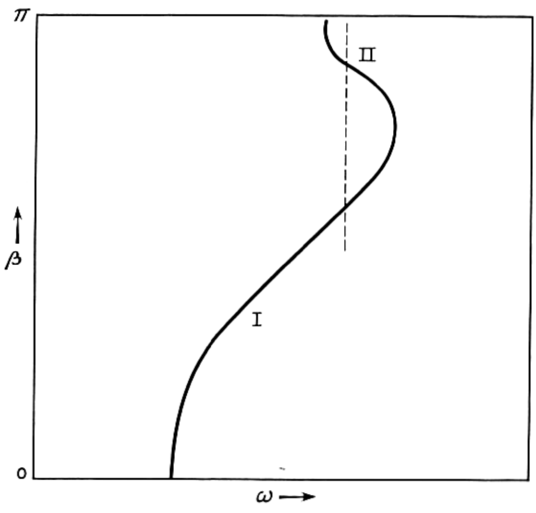

Fig. 5 — Double mode of propagation.

velocities have opposite directions. In our design we wished to use a narrow passband and consequently the loading was chosen such that small changes in the loading could shift the structure from forward to backward. Under these conditions curves such as shown in Fig. 5 can occur. Notice that the upper and lower cutoff frequencies are close together as indicated by the 0 and π phase-shift points. However, in the nominal passband of the structure the phase shift is double-valued.

This double mode has a particularly bad effect upon a traveling-wave maser. Consider operation at a frequency within the double mode region as indicated by the dotted line of Fig. 5. The mode labeled I has a forward phase velocity and a forward group velocity. With the correct direction of magnetic field and an isolator, we will obtain normal unilateral gain in the forward direction. However, under the same conditions, unilateral gain in mode II will be in the reverse direction because the group velocity is backward for the phase velocity which corresponds to low isolator loss. Oscillation can now occur—the wave travels forward in the structure on mode I, is reflected by any mismatch into mode II, and returns to the input of the amplifier on mode II. The result is a feedback path with potentially high gain.

These effects have since been encountered in masers at other frequencies when attempting to obtain very narrow bandwidths. Frequently a change of only a few mils in the dielectric loading is sufficient to cure the difficulty.

REFERENCES

1. Jakes, W. C., Jr., Participation of Bell Telephone Laboratories in Project Echo and Experimental Results, this issue, p. 975.
2. Crawford, A. B., Hogg, D. C., and Hunt, L. E., A Horn-Reflector Antenna for Space Communication, this issue, p. 1095.
3. Ohm, E. A., Receiving System, this issue, p. 1065.
4. DeGrasse, R. W., Schulz-DuBois, E. O., and Scovil, H. E. D., The Three-Level Solid State Traveling-Wave Maser, B.S.T.J., **38,** 1959, p. 305.
5. Geusic, J. E., Microwave Solid-State Devices, U. S. Army Signal Corps Contract DA-36-039 sc-73224, Tenth Interim Report, August 1959.
6. Schulz-DuBois, E. O., Microwave Solid-State Devices, U. S. Army Signal Corps Contract DA-36-039 sc-73224, Eleventh Interim Report, November 1959.