A UHF Solid-State Maser*

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Summary—Chromium doped potassium cobalticyanide has been utilized in the design and construction of a solid-state maser operating in the frequency range of 300 to 500 mc. The pumping frequency is fixed at 5400 mc and the magnetic field required is in the vicinity of 80 gauss. The design utilizes a cavity mode at the pumping frequency and a tuned loop at the operating frequency, thus avoiding the design complications associated with the large size of UHF cavities. System measurements using a directional coupler for isolation yield noise temperatures of approximately 70 degrees Kelvin at bandwidths in the 50 kc range.

INTRODUCTION

THE operation of a maser using potassium chromicyanide was first described by McWhorter and Meyer.[1] Their device amplified at 2800 mc and used a pumping frequency of approximately 9000 mc. With the success of this mode of operation, it seemed possible to extend the operating range down to frequencies in the UHF region on the basis of extrapolation of the parameters of the initial maser design. The new design involves two major considerations. One is the choice of a suitable region in the paramagnetic energy level scheme of the crystal, while the other is the choice of a doubly resonant structure to support both the pumping and amplifying frequency resonances.

CRYSTAL OPERATING REGION

With 300 to 500 mc as the desired range of amplifying frequencies, the most apparent operating point is near the zero magnetic field range of the energy levels. Although appropriate transitions might be found in the 1000 to 2000 gauss region,[1] the variation of the spacings with field and angular orientation is extremely complicated. In addition the operation of a maser with fields of the order of a hundred gauss was attractive from the instrumentation point of view. (Another advantage connected with the use of superconductivity will become apparent below.) In Fig. 1 is the energy level diagram for two orthogonal orientations of the crystal in the zero-field region. By variation of the angle of the magnetic field with respect to the principal magnetic axis, it is possible to obtain the lower transition anywhere from 300 up to 1000 mc, while maintaining the pump frequency constant in the vicinity of 5400 mc. The theoretical gain-bandwidth to be obtained in this mode of operation may be calculated most directly by comparison with the results of McWhorter and Meyer's experiments. For the same crystal, the magnetic Q, or $|Q_M|$ is inversely proportional to $(f_{\text{pump}}-2f_{\text{ampl}})$, while the gain-bandwidth product is given by[1]

$$G^{1/2}B = 2f_{\text{ampl}}/|Q_m|.$$

Since McWhorter and Meyer obtained a value of approximately 2×10^6 sec^{-1} for this figure, the expected value at 300 mc would be

$$\frac{5400-2(300)}{9400-2(2800)}\times\frac{300}{2800}\times 2\times 10^6 = 0.27\times 10^6 \text{ sec}^{-1}$$

assuming the same filling factor and equal values for the spin-lattice relaxation times.

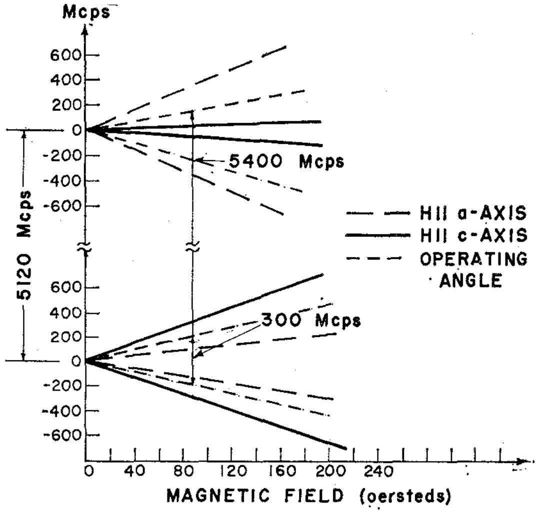

Fig. 1—Energy levels at low field in potassium chromicyanide.

DOUBLE RESONANT STRUCTURE

Previous maser designs have utilized a microwave cavity which resonates both at the pumping and amplifying frequencies. It would be possible to build such a cavity for this design; however, the 18 to 1 ratio of frequencies places severe restrictions on the type of cavity which can be used. In particular, a straightforward coaxial $\lambda/4$ cavity at 300 mc is not only inconveniently large, but the 5400 mc mode would have so many nulls in the RF magnetic field that only a small part of the cavity volume could be used, thus lowering the filling factor. It is possible to foreshorten the low-frequency mode by heavy capacitative loading at the open circuited end as was done by Autler and McAvoy;[2] how-

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[1] A. L. McWhorter and J. W. Meyer, "Solid-state maser amplifiers," *Phys. Rev.*, vol. 109, pp. 312–318; January, 1958.

[2] S. H. Autler and N. McAvoy, "21-centimeter solid-state maser," *Phys. Rev.*, vol. 110, pp. 280–281; April, 1958.

ever, the much higher frequency ratio here required presented much more serious design problems. As an alternative, it was decided to forego a cavity mode at the lower frequency and use a single-turn loop terminated in a lumped capacitance. The dimensions and configuration of this resonant circuit, shown in Fig. 2 were chosen such that the RF magnetic field of the loop could be completely immersed in the RF magnetic field of a 5400 mc cavity mode. By placing the crystal, a cylinder 1.5 cm in diameter and about 2 cm long, such that the ac plane lies in the plane of the loop, most of the RF magnetic field will be perpendicular to the applied dc magnetic field, thus assuring close to the optimum transition probabilities. The dc field may also be rotated in the plane of the loop for tuning of the two resonances. This configuration when placed in a TE_{112} mode cavity, as shown in Fig. 3, was found to have only a small effect upon the unloaded Q of the 5400 mc mode. This mode was chosen since the resultant RF magnetic field at the center of the cavity lies in the plane of the loop and thus does not couple energy out of the mode.

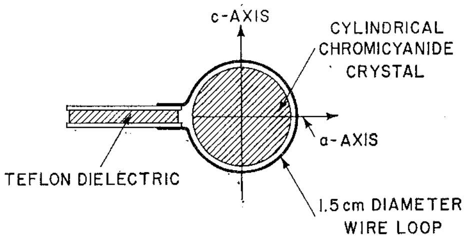

Fig. 2—300 mc resonant circuit.

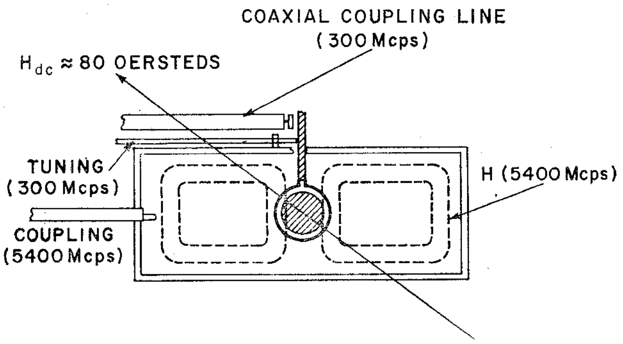

Fig. 3—Final maser assembly, cylindrical cavity (TE_{112} mode). The capacitor plate opposite the two probes is grounded to the cavity wall.

Although the resultant Q of the pumping mode was sufficiently high, that of the wire loop circuit was only about 200 even at liquid helium temperatures. Since the negative Q of the maser material was expected to be of the order of 1000, it was essential that the loop losses be diminished so that the unloaded Q would be much greater than $|Q_M|$. This improvement was obtained by the simple expedient of plating the loop and capacitor plates with lead, which is a superconductor at helium temperature. The resultant unloaded Q was of the order of 10,000. This technique is, of course, dependent upon the low magnetic fields used in the design, since lead ceases to be a superconductor in fields from 600 to 800 gauss in the 4.2 to 0 degrees Kelvin range. Another phenomenon of superconductivity can present difficulties. This is the Meissner effect, the shielding of the magnetic field by a superconducting material. Since the loop is a thin wire and the magnetic field lies in the plane of the loop, this effect is not of a serious nature.

EXPERIMENTAL RESULTS

The instrumentation and mechanical equipment associated with the maser are similar to those used by McWhorter and Meyer with the exception of the actual frequencies. As shown in Fig. 3, both frequencies were coupled to the cavity by means of coaxial lines of silver plated stainless steel inner and outer conductor. In addition, fine tuning of the 300 mc mode was accomplished by external adjustment of the grounded capacitative probe between the coupling line and the cavity. The magnetic field was supplied by a six inch inner diameter wire-wound coil which could be tilted so that the field always lay in the plane of the 300 mc loop. The dc power requirement was 10 volts at 2.5 amperes. Provisions were also made to pump on the liquid helium so that the temperature of the bath could be lowered to 1.25 degrees Kelvin.

The maser was operated initially at 1.6 degrees Kelvin and 300 mc and yielded an oscillator output of approximately 0.1 microwatt. The gain at 100 kc bandwidth was approximately 10 db, giving a gain-bandwidth product of 0.32×10^6 sec^{-1}. Later measurements at 450 mc and 1.25 degrees Kelvin yielded gains as high as 25 db, in this case with a bandwidth of the order of 30 kc. This corresponds to a gain-bandwidth product of about 0.5×10^6, consistent with the higher frequency and the lower operating temperature. These numbers are in quite good agreement with McWhorter and Meyer's data which was taken at 1.25 degrees Kelvin with the same crystal material (0.5 per cent chromium concentration). The slightly higher values are consistent with the higher filling factor obtainable with the cylinder-loop configuration, although marked changes in the $|Q_M|$ could have occurred as a result of small differences in the three relaxation times involved.

SYSTEM PERFORMANCE

The theoretical noise contribution of such a maser in a system is of the order of 0.1 degree Kelvin. It should be noted that temperatures below the bath temperature are quite feasible since the high pumping ratio produces a "negative temperature" much smaller than the true positive temperature of the equilibrium electron distribution. With such a low theoretical value it was quite apparent that any serious noise sources in an amplifier system would arise in the associated circuitry and not in the maser crystal itself. As a test of the low-noise performance the maser was connected to a 450 mc antenna system and low-noise receiver, as shown in Fig. 4. In this method of operation the maser is isolated from the receiver input noise by a directional coupler. The ideal method utilizing a circulator is not possible since such devices are not available at these frequencies. Here 10 db of gain is sacrificed with the advantage of 10 db attenuation of the receiver noise before it enters the maser. A disadvantage is the large reflected signal returned to the antenna terminals; however, the double stub tuner provided an adequate enough match to prevent serious gain fluctuations even when the antenna was moved through its total azimuth and elevation range. Independent radiometer measurements of the antenna system had established that the effective noise at the antenna terminals was 100 degrees Kelvin, when the antenna was pointed at quiet sky. (Sky temperatures off the galactic plane at this frequency are approximately 20 degrees Kelvin.) The remaining 80 degrees Kelvin may be attributed to antenna side and back-lobe pickup and loss in the transmission line between the feed horn and the receiver installation. The receiver had a noise figure of 4.8 db, corresponding to 600 degrees Kelvin excess noise. By injecting a measured amount of noise signal from a gas tube into the antenna line by means of a directional coupler, the noise temperature of the over-all maser system was found to be 170 degrees Kelvin. This corresponds to a noise figure of $(1+170/300)=1.57$ or 2 db. When working with cold antennas, it should be remembered that the conventional noise figure definition is misleading, since in this case, the improvement from 4.8 db down to 2.0 db corresponds to an improvement in sensitivity of $(600+100)/(170)$ or 6.1 db. The experimental value checked quite well with the theory, using a maser gain of 25 db, as estimated from independent measurements. The noise sources referred back to the antenna terminals are:

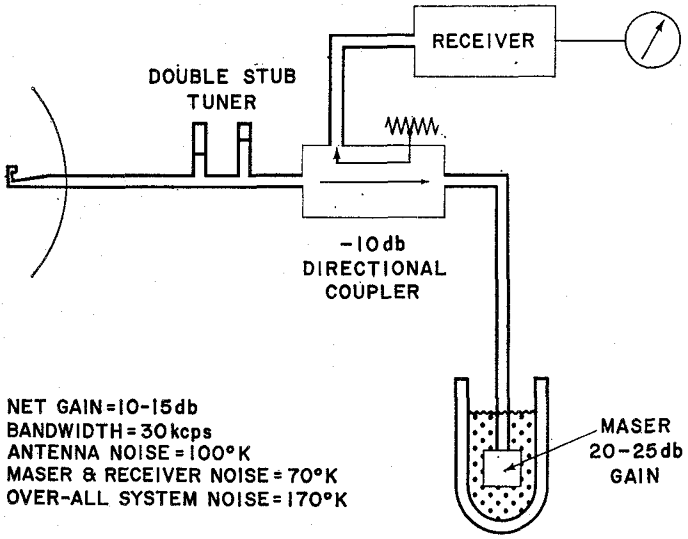

Fig. 4—Maser system measurement.

Antenna and transmission line = 100°K
Receiver output noise—600°K down 15 db = 20°K
Receiver noise into maser—400°K down 10 db = 40°K
Termination in directional coupler—300°K down 15 db = 10°K
Total excess noise referred to antenna terminals = 170°K

The receiver noise generated at the input terminals was measured independently with a radiometer and found to be 400 degrees Kelvin as used in the above calculations. This figure applies only to the particular input circuit used, a grounded-grid 416B. It is quite probable that a crystal mixer input, for example, might have an entirely different effect upon the performance, even though the over-all noise figure of the receiver were the same.

CONCLUSION

The experiments established the fact that a maser could be operated successfully in the UHF range in a reception system, with much lower noise than hitherto obtainable with standard receiver systems. There are, however, serious shortcomings to the system as presently operated. These are:

1) Lack of circulators or isolators in the UHF range. The ultimate in low noise could be obtained with these devices, as well as the elimination of instabilities arising from the high VSWR on the antenna line.
2) Narrow bandwidth. Although suitable for some applications, the critical tuning and lack of flexibility associated with the narrow bandwidth present serious system design problems.
3) Saturation sensitivity. Since the oscillator power output is only 0.1 microwatt it follows that the maser will saturate on incoming signals equal to this level divided by the maser gain. This means that radar use would require duplexer protection down to approximately 10^{-9} watts. Otherwise, the maser would not recover from the leakage pulse for approximately 0.1 second, the lattice relaxation time.
4) Antenna noise. Previously unimportant, the noise generated by the antenna and associated transmission system is now the main limiting factor and will require serious studies to assure optimum design for use with masers.

ACKNOWLEDGMENT

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