least between fields from 50 to 200 v/cm. Within this range of fields, therefore, there is no trace of the marked dependence of mobility on E claimed by Careri *et al.*[1] The ratio μ_-/μ_+ of negative- to positive-ion mobilities is slightly temperature-dependent; e.g., its value decreases from 0.77 at 2°K to 0.62 at 1.18°K. The exact nature of the ions is not known. They may well be complexes more complicated than simple He^+ or He^- ions.[5]

The striking increase of μ with decreasing temperature shown in the logarithmic plot of Fig. 3 suggests the correlation $\mu \sim \rho_n^{-1}$ with the density of the normal fluid. This is what one might expect from a simple model in which the ion mean free path varies inversely with the number of scattering excitations (predominantly rotons above 1°K) where these are not too dense, i.e., at temperatures sufficiently below the λ point. Putting approximately $\rho_n \sim e^{-\Delta/kT}$ for the roton contribution to the normal fluid density[6] in the temperature range of interest, the slope of the μ_+ curve in Fig. 3 yields $\Delta/k = 8.3$°K. This lies within the spread of values for Δ/k deduced from measurements of ρ_n by different methods. Thus oscillating disk techniques yield $\Delta/k = 10.6$°K, whereas the combination of second sound and thermal data gives lower values in the range $\Delta/k = 8$—9.6°K.[7] On the other hand, in He I or just below the λ point where the excitations are very dense, one might expect to be able to consider He like an ordinary liquid. In that case one expects $\mu \sim \eta^{-1}$ on the simple model of a quasi-macroscopic charged sphere being dragged through a medium of viscosity η.[8] The approximate constancy above 2°K of the product $\mu_+\eta$ shown by the dotted curve in Fig. 3 may lend some support to this naive picture.

It is planned to extend these measurements with improved techniques to temperatures below 1°K and to the rotating fluid.

* This work was supported in part by grants from the National Science and the Alfred P. Sloan Foundations.

[1] Careri, Reuss, Scaramuzzi, and Thomson, Proceedings of the Fifth International Conference on Low Temperatures, Madison, Wisconsin, August, 1957 (unpublished), p. 79.

[2] A. M. Tyndall and C. F. Powell, Proc. Roy. Soc. (London) **A129**, 162 (1930).

[3] We are indebted to Dr. J. L. Richmond of the Mound Laboratory, Monsanto Chemical Company, for kindly preparing the Po source for us.

[4] If absolute values of the mobilities were of interest, the scale factor could be determined by making these measurements for two different values of the spacing d between A' and B. The *difference* in drift distance would then be known and unaffected by edge effects near the grids which cancel.

[5] For example, in He gas He_2^+ ions predominate over He^+ ions at the higher pressures [A. V. Phelps and S. C. Brown, Phys. Rev. **86**, 102 (1952)], and have higher mobilities than the latter since they are distinctly different from the neutral atoms and hence do not suffer resonant charge exchange scattering.

[6] I. M. Khalatnikov, Uspekhi Fiz. Nauk S.S.S.R. **59**, 673 (1956).

[7] J. G. Dash and R. D. Taylor, Phys. Rev. **105**, 7 (1957).

[8] J. Frenkel, *Kinetic Theory of Liquids* (Oxford University Press, New York, 1946), p. 193.

21-Centimeter Solid-State Maser*

S. H. Autler† and Nelson McAvoy‡
Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts

(Received February 3, 1958)

A 3-LEVEL solid-state maser[1] using $K_3Co(CN)_6$ doped[2] with $\frac{1}{2}\%$ $K_3Cr(CN)_6$ has been operated as an amplifier at 1382 Mc/sec. The design is somewhat different from a previously reported one which operates in the same frequency range.[3] Saturating power is supplied at 9070 Mc/sec through a wave guide while a coaxial line terminated in a probe serves as both input and output for the amplified power. The band width has been varied from about 1 Mc/sec to less than 50 kc/sec by changing the probe insertion and thus the external coupling. At an operating temperature of 1.25°K the product of voltage gain and band width is about 1.85×10^6 sec^{-1} over a considerable range.

A means of obtaining a reasonably large filling factor and still saturating all spins is to use a cavity with dimensions small compared to a wavelength at the signal frequency. With a coaxial cavity (Fig. 1) shortened by capacitative loading at one end, a filling factor of approximately 0.5 is obtained. Pumping is possible in several higher-order modes but best results were obtained for the 9070-Mc/sec mode.

The maser operates at a magnetic field of about 1200 gauss, making an angle of 18° with the a axis and 90° with the b axis of the crystal.[2] It can be seen from Fig. 2 of reference 2 that in this region emission can occur between levels 2 and 3 and saturation between 2 and 4, where the levels are designated in order of increasing energy.

It is of some interest that we were unable to make a maser amplifier work using the same cavity and a crystal containing 1% Cr. The reason for this is not yet understood, but a possible explanation is that the additional power required for saturation at the higher concentration raises the lattice temperature, reducing the spin-lattice relaxation time, which results in still greater power requirement for saturation, etc.

The measured gain band width product is less than one-fifth the theoretical value for $\Delta M = \pm 1$ transition.

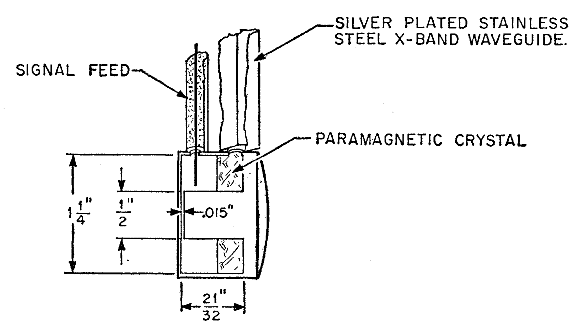

Fig. 1. Cross-sectional view of maser cavity.

Although a calculation of the wave functions in the operating region would be quite involved, it is likely that mixing of the states has greatly reduced the transition probability between levels 2 and 3. Relatively weak paramagnetic absorption observed in the absence of saturating power confirms this, and better maser performance should be obtainable by operating at lower magnetic fields (200–300 gauss) where stronger absorption is observed. This would require a somewhat lower pumping frequency than 9 kMc/sec.

About 28 milliwatts of saturating power is required, which is considerably greater than that reported by McWhorter and Meyer.[2] A reduction should be obtained by using a cavity mode at the saturating frequency which has no magnetic field nodes within the crystal.

A new design for a tunable maser which incorporates these improvements is being constructed and may be useful in radio astronomy for observing Doppler-shifted hydrogen radiation.

* The research reported in this document was supported jointly by the Army, Navy, and Air Force under contract with the Massachusetts Institute of Technology.

† Staff Member, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts.

‡ Visiting staff.

[1] N. Bloembergen, Phys. Rev. **104**, 324 (1956).

[2] A. L. McWhorter and J. W. Meyer, Phys. Rev. **109**, 312 (1958).

[3] Ortman, Bloembergen, and Shapiro, Phys. Rev. **109**, 1392 (1958).

Two-Level Solid-State Maser*

P. F. Chester, P. E. Wagner, and J. G. Castle, Jr.

Westinghouse Research Laboratories, Pittsburgh, Pennsylvania

(Received February 6, 1958)

MICROWAVE amplification and oscillation have been observed at 4.2°K using two-level electron spin systems.[1] The materials used were single crystals of quartz and of magnesium oxide, each containing paramagnetic defects introduced by neutron irradiation.[2,3]

Samples were mounted in a reflection cavity resonant at 9 kMc/sec and having a loaded Q of ~6000. Inversion of the electron populations was brought about by adiabatic rapid passage,[4] in which the magnetic field was swept through resonance. The field sweep also prevents excessive radiation damping[5] immediately after inversion by taking the Larmor frequency off cavity resonance.[6] Microwave power for the inversion was supplied in pulses of 50 to 100 μsec duration and about one-half watt amplitude at a repetition rate of 10 cps. For convenience, inversion and amplification were observed as the magnetic field was swept back through resonance at a controlled delay after the inverting sweep. Under these conditions the duration of the amplifying period was controlled by the rate of the return field sweep. The power reflected from the cavity was monitored with a frequency-stabilized cw klystron and a superheterodyne detector.

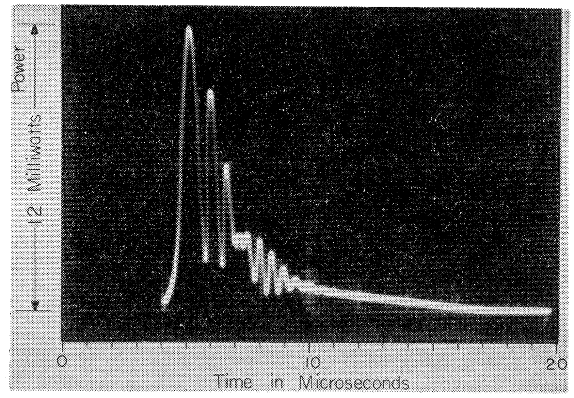

Fig. 1. Power emitted from cavity under oscillation conditions as the magnetic field is swept through resonance after inversion.

With a quartz sample containing $\sim 10^{18}$ spins, the inverted state persisted for 2 milliseconds at 4.2°K; and regenerative amplification occurred for times up to 1.2 milliseconds after inversion, the gain decreasing with time. A value of $\sim 5\times 10^6$ sec^{-1} was obtained for the product $(\text{gain})^{\frac{1}{2}}\times$band width, for gains between 8 and 21 db. With sufficient inverting power and with or without monitoring power, oscillation was observed on the return through resonance. The peak power emitted during oscillation was 12 milliwatts in a pulse of about 10 microseconds duration. Figure 1 shows a typical oscillation pulse. The structure of the pulse may be associated with field inhomogeneities known to be present. Similar structure has been reported for spontaneous emission in doped silicon by Feher *et al.*[7] After an oscillation pulse, amplification was still observed when subsequent field sweeps were applied. Figure 2 shows the result of repeated field sweeps at 130-microsecond intervals. The wide signal on the left is caused by the inverting pulse. The signal occurring on the second sweep is oscillation. The next eight signals represent amplification each time the field passes through resonance, the gain falling from 16 db on the third sweep to 6 db on the seventh and to less than 0 db on the eleventh.

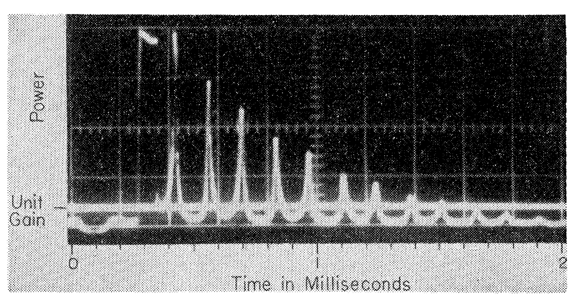

Fig. 2. Power reflected from cavity as a function of time after inversion as magnetic field is swept repeatedly through resonance. Horizontal trace represents unity power reflection. The inverting pulse and the oscillation peak both saturate the detector. Monitoring power: 4×10^{-8} watt.