IV. MICROWAVE SPECTROSCOPY

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RESEARCH OBJECTIVES

The microwave spectroscopy laboratory studies matter – gases, liquids, and solids – by examining the interaction of matter with radiofrequency and microwave-frequency radiation. Much of the work at the present time uses paramagnetic materials, either as impurities or as the total matter, to provide the link between the electromagnetic radiation and the matter.

This work leads to an understanding not only of the energy levels of the system itself, but also of the coupling between the nearly commuting elements that form the total system. Thus, in paramagnetic solids we have been studying not only the appropriate descriptions of the paramagnetic states of the solids, but also the appropriate description of the coupling between the spin states and the lattice modes of vibration.

Although considerable effort has been placed upon understanding the application of paramagnetic crystals to the new field of quantum-mechanical amplifiers, particularly upon understanding their operation and characteristics, such as gain-bandwidth product and noise figure, we have also investigated the operating properties of these devices. Operation of quantum-mechanical amplifiers, measurement, and development of a further understanding of their basic properties will continue. The impact of this work on modern technology is so dramatically imminent that an examination of our work and the work of others in this field demonstrates how short the time interval between basic research and technological integration can be made.

M. W. P. Strandberg

A. AMMONIA MASER*

The parts of the maser were tested, and the microwave circuits and electronic equipment were set up for the detection of the extremely small signal from the ammonia beam. The superheterodyne method of detection has been employed with a tuned amplifier for the intermediate frequency at 40 mc. Highly attenuated 23.87-kmc power is supplied to the maser cavity and reflected from it. The local oscillator operates at 23.91 kmc. The signals from the maser and the local oscillator are mixed in the crystal. The signal with the frequency difference of 40 mc is amplified and observed on an oscilloscope.

The maser cavity has a resonant frequency of 23.88 kmc under normal conditions (temperature, 25° C). It is cooled inside the vacuum chamber to liquid-nitrogen temperature and electrically heated so as to resonate at the 3-3 inversion frequency of ammonia. Approximately 4.5 watts are supplied to the cavity heater for this purpose.

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The beam source inside the vacuum chamber is supplied with a power of approximately 5 watts for heating, in order to prevent the ammonia from condensing on the channel source. The ammonia beam is formed in the vacuum chamber by bubbling the gas through the Octoil at the rate of one bubble per second, so that there is a pressure of approximately 0.3 mm behind the channels of the beam source.

Search for the emission line is being carried out.

H. G. R. Venkatesh

B. PARAMAGNETIC-RESONANCE SPECTROMETER

A paramagnetic-resonance spectrometer that can be made preferentially sensitive to either the paramagnetic absorption or the associated paramagnetic dispersion has been constructed. The conventional spectrometer that was previously used is insensitive to dispersion because the microwave oscillator is frequency-"locked" to the sample cavity. In this new spectrometer the microwave oscillator is "locked" to an auxiliary cavity. The absorption modulated signal from the matched sample cavity contains terms proportional to χ' and χ'', the absorption and dispersion. Preferential detection of either of them is achieved by mixing the signal with a reinjected carrier of adjustable phase before detection by the microwave crystal.

The theory of operation of this spectrometer has been worked out and is being checked experimentally. Its sensitivity as compared with the conventional spectrometer that is in use will be obtained, and an absolute sensitivity determination for both systems will be made.

G. J. Wolga, B. Josephson, Jr.

C. VERSITRON 180°-PULSE TECHNIQUE*

Partial population inversion has been achieved on crystals of ammonium chrome alum and gadolinium ethyl sulphate at liquid-helium temperature and at a frequency of 9000 mc. Since the resulting negative resistance was not sufficient to overcome cavity losses, gain was not achieved. Emphasis has been placed on improving the short-pulse generator and the detection equipment.

The short-pulse generator uses a resonant length of microwave transmission line as a pulse-forming network. This resonator is discharged by means of a spark-gap switch. The first version of this pulser used a switch that was triggered by a microwave signal from the same magnetron that excited the line resonator. The triggering signal was delayed by a microwave delay network. This first system was used for the first inversion runs. It offered economy of components but was never entirely

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satisfactory. The three-point spark gap that was used was critical to adjust.

The present short-pulse generator uses video triggering of the microwave spark. The gap terminals are hemispheres with a trigger pin inside one terminal. Reliable operation was achieved with this system and the pulser is considered satisfactory. Although the microwave pulse length has not been measured, there is reason to believe that it is less than 10 mμsec.

No further development of this short-pulse generator is planned. The minimum pulse length of such a pulser is determined by the spark rise time. Research on this aspect of the problem might be undertaken at some future time if it seems necessary. A detailed description of the short-pulse generator follows.

An extremely short (millimicrosecond) pulse is formed by storing microwave energy in a cavity and then discharging it rapidly to the load. A schematic diagram of the short-pulse generator is shown in Fig. IV-1. The cavity is formed from a length of waveguide with a short circuit at one end and a magic tee at the other. Power from a magnetron is coupled in through an iris on the side of the cavity at a point located near the magic tee. By construction, arms 3 and 4 of the tee are identical. The bridge thus formed is balanced, and an effective short circuit is provided at that end of the cavity. A photograph of the magic tee is shown in Fig. IV-2; a cross-section drawing, with a detail of the spark-gap arrangement, in Fig. IV-3.

Energy is fed into the cavity until equilibrium fields are reached. This time coincides with the end of the magnetron pulse. A spark is fired at a point located at an odd number of quarter wavelengths from the end of one of the arms of the magic tee (arm 3 in Fig. IV-2) and unbalances the bridge. Ideally, the tee (and load) with the gap, when fired, presents a match to the resonant section of the line. The energy in the cavity, considered as two waves traveling in opposite directions, then flows out of arm 2 to the load. The pulse duration is equal to twice the time that it takes for a wave to travel from one end of the cavity to the other. Different pulse lengths are obtained by using different lengths of waveguide for the cavity.

The spark in arm 3 is set off through a small hole in the gap by a trigger spark outside the waveguide. The trigger spark is fired by a conventional trigger generator. An iris is placed around the main spark gap to form a resonant slot.

The sample cavity which was used for all of the runs is a cylindrical cavity with two orthogonal polarizations of the TM_{110} mode. It is filled with fused quartz to bring down its size to the dimensions of the cryostat. Two waveguides are used, with one coupled to each mode. The crystal is mounted along the cavity axis, in which position it is in the magnetic-field maximum. The microwave magnetic fields of the two modes are normal to each other and to the dc magnetic field. The mode used for measurement of susceptibility has a Q_o of approximately 5000 at room temperature. The spin-flipping mode is loaded by the waveguide to a Q of 40 so that it can respond to very short pulses.

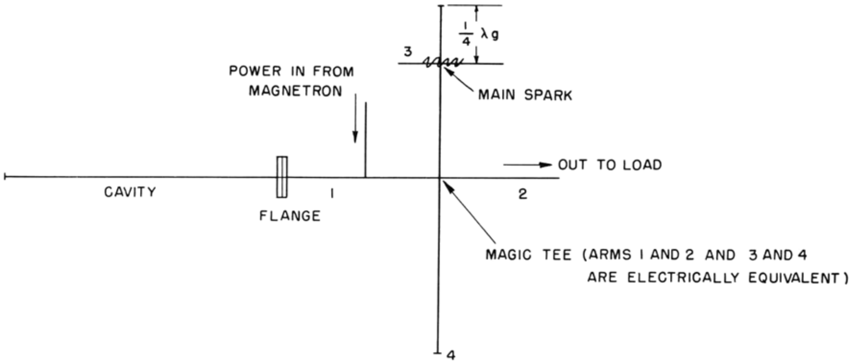

Fig. IV-1. Schematic diagram of short-pulse generator.

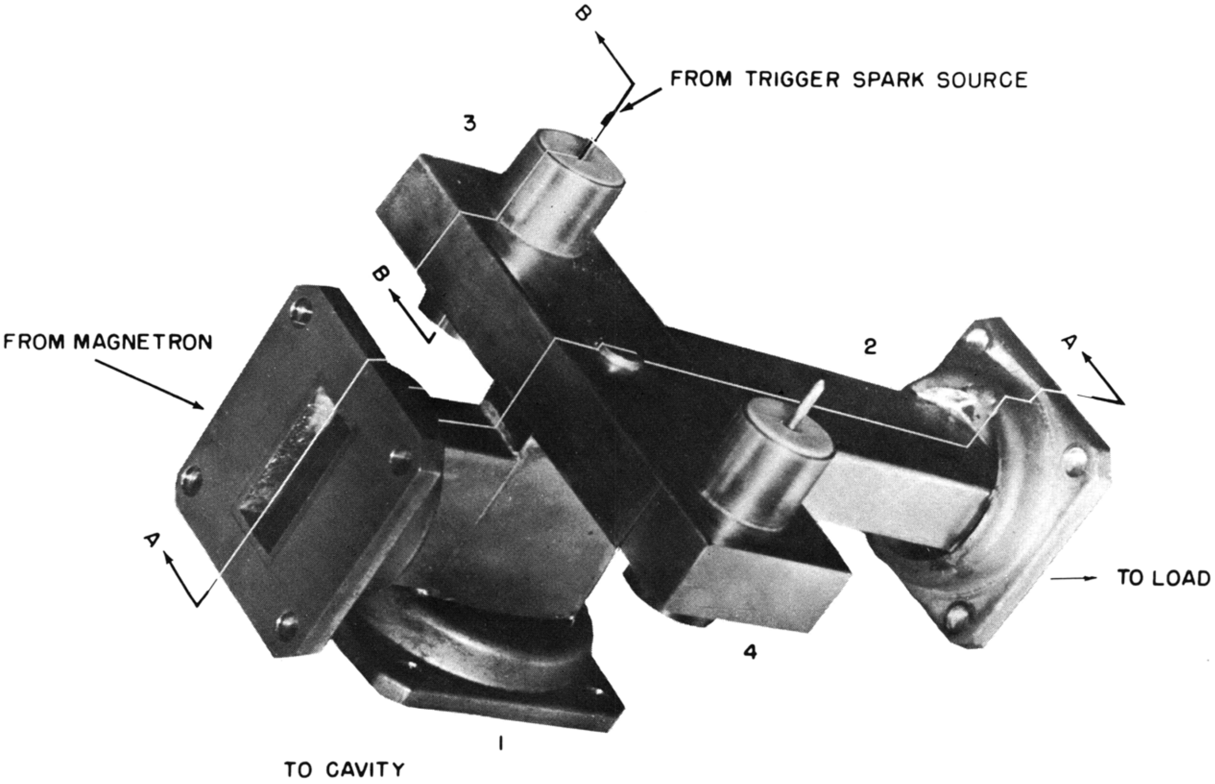

Fig. IV-2. Photograph of short-pulse generator (without cavity).

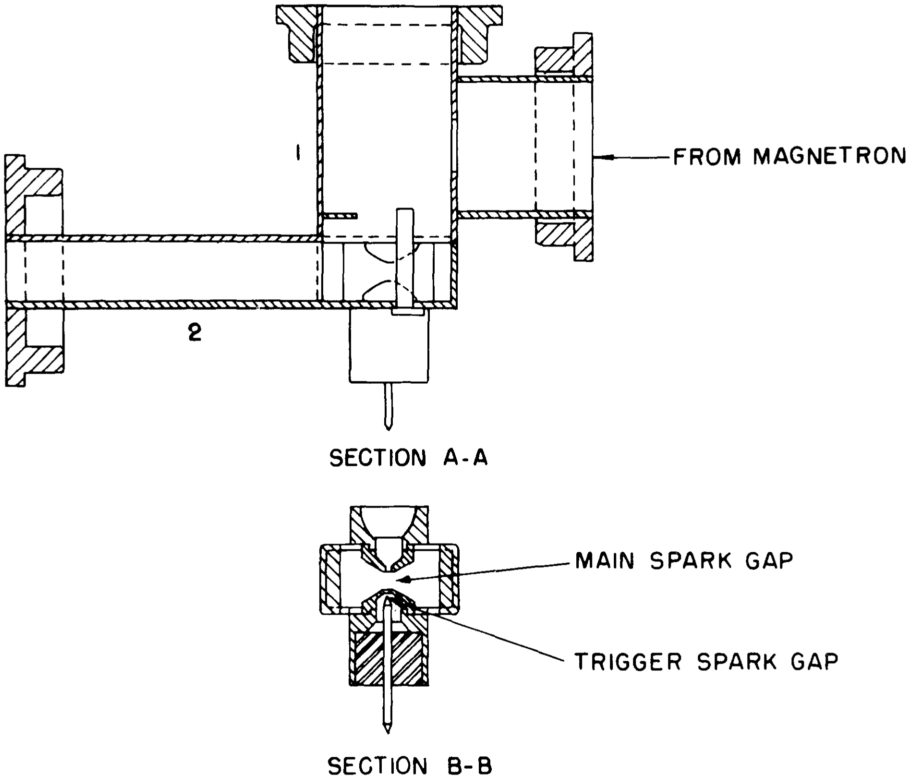

Fig. IV-3. Cross-section view of short-pulse generator, with detail of spark-gap arrangement.

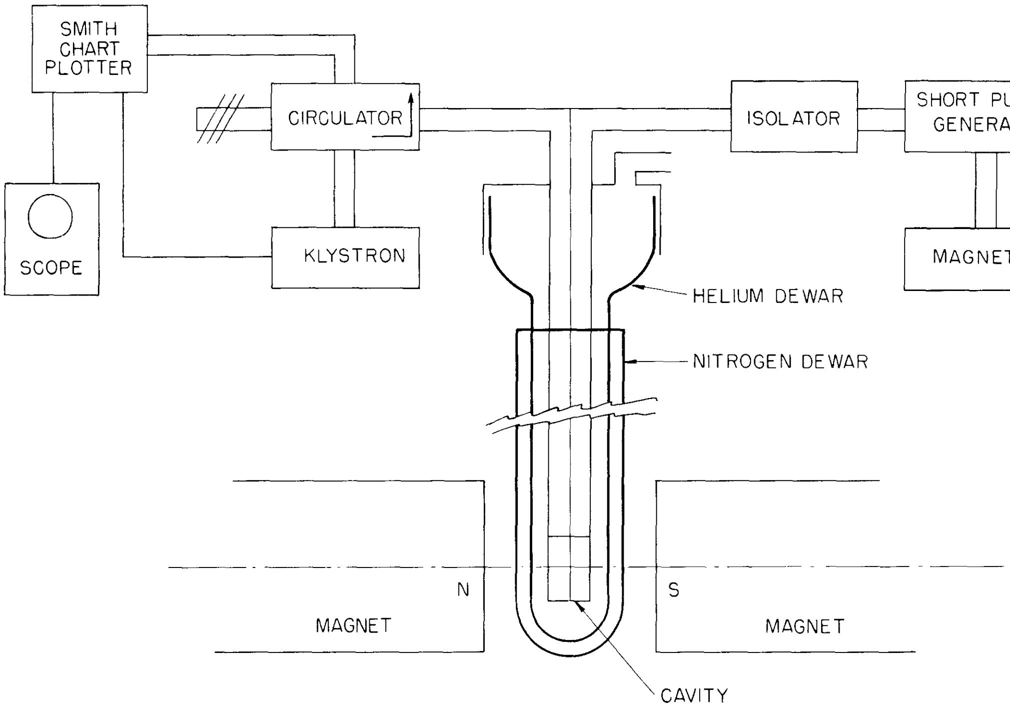

Fig. IV-4. Schematic diagram of equipment.

Dewars are arranged so that measurements can be made at liquid-helium temperature. Figure IV-4 is a schematic diagram of the experimental apparatus.

The method of observation was that of making conventional impedance measurements. No modulation procedures are necessary, since a crystal which is capable of amplification must have an easily detectable paramagnetic resonance. Point-by-point measurement was found to be time-consuming and was made more difficult by line-length drifts as the helium evaporated. To meet this problem, an electronic Smith-chart plotter was developed. Commercial Smith-chart plotters are not fast enough to follow the relaxation time T_1 of the crystal. The system developed here uses 30-mc circuitry and has a response time of a few microseconds. The finishing touches are being put on the device; a detailed description will be given in a later report. A crudely constructed model has already demonstrated its worth by displaying some unsuspected features in the spin-flipping behavior of chrome alum. Its operation will now be described.

The output of a klystron is modulated at 30 mc — one sideband and the carrier being separated for use as the measuring signal and local-oscillator signal in a superheterodyne detection system. The measuring signal is applied to the cavity, the reflected wave going to the mixer of the i-f system. The 30-mc signal from the i-f amplifier is split and detected with the in-phase and quadrature signals from the 30-mc oscillator. These signals give the in-phase and quadrature components of the reflection coefficient, which are applied to the two axes of an oscilloscope.

This Smith-chart plotter has a much faster response time than existing commercial models. This speed is necessary for observing the rapidly varying spin population in pulsed paramagnetic experiments.

Several flipping runs were made with the old pulser on gadolinium ethyl sulphate and ammonium chrome alum. The change in cavity Q immediately after the application of the flipping pulse indicated that an inverted population had been achieved. For gadolinium ethyl sulphate, the best run gave a negative temperature of approximately -11° K for the paramagnetic transition that was being flipped, compared with the temperature of -4° K which would result from complete population inversion. We estimate that a temperature of -4.8° K will be necessary for oscillation with the spin concentration and cavity Q that were used.

One run was made on the same chrome alum crystal with the new pulser and the Smith-chart plotter. It indicated that a significant contribution to the susceptibility of the sample was coming from two neighboring lines of the paramagnetic spectrum.

The next objective is, clearly, to obtain paramagnetic crystals with narrower lines than those of the crystals that we used in these first attempts.

R. L. Kyhl, S. A. Collins, Jr., D. J. M. Park, Jr.

D. SOLID-STATE QUANTUM-MECHANICAL AMPLIFIER[*]

An S-band solid-state quantum-mechanical amplifier has been operated at 4.2° K with a computed noise temperature of less than 4.5° K. There are indications that operation at a still higher temperature is feasible and is potentially capable of yielding higher output powers. This device has operating characteristics similar (e.g., gain-bandwidth product) to the one previously built by McWhorter and Meyer (1).

Considerable information was derived by noting the orientation and appropriate selection rules for the pumping frequency. McWhorter and Meyer saturated a line that was almost degenerate with the pumping transition; this saturated line, in turn, saturated the pumping transition. This effect can best be accounted for by demonstrating that a narrow-band lattice-phonon saturation can effectively couple the two transitions. By analyzing the operation of another maser (2), it is possible to estimate that phonon saturation occurs in a band less than 600 mc wide.

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R. L. Kyhl, G. J. Wolga

References

1. A. L. McWhorter and J. W. Meyer, Phys. Rev. (to be published).
2. H. E. D. Scovil, G. Feher, and H. Seidel, Phys. Rev. 105, 762 (1957).

E. GADOLINIUM ETHYL SULPHATE SPECTRUM

The paramagnetic-resonance spectrum of the trivalent rare earth ion, gadolinium, modified by its crystalline surroundings, is being investigated. The ground state of the free ion is ${}^8S_{7/2}$ and the effect of a crystalline potential with hexagonal symmetry is to break down the eightfold degenerate ground state into four doubly degenerate states, these final degeneracies being removed by an external magnetic field.

Expansion of the crystalline potential as a sum of spherical harmonics and assumption of a crystal symmetry that is characteristic of the C_{3v} group enables us to describe the interaction of the free ion with its surroundings and with an external magnetic field, by means of the following "spin Hamiltonian"

$$H = g\beta\vec{H} \cdot \vec{S} + B_2^0P_2^0 + B_4^0P_4^0 + B_4^3P_4^3$$

$$+ B_6^0P_6^0 + B_6^3P_6^3 + B_6^6P_6^6$$

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The effect of including the off-diagonal elements in the energy matrix, the P_4^3, P_6^3, and P_6^6 terms, should become apparent when the magnetic field is normal to the crystal symmetry axis. We hope to make a quantitative estimate of the magnitude of these terms by comparing an exact diagonalization of the energy matrix with the observed spectrum.

J. J. McNicholl