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THE APPLICATION OF MASERS TO PHYSICAL MEASUREMENTS*

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ABSTRACT

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The use of masers as low noise preamplifiers in microwave communications is well known. This paper describes the use of masers in physical measurements. In particular, the changes in spin-temperature of a paramagnetic crystal as a function of various perturbations have been measured.

Both spin "heating" and spin "refrigeration" of the order of 1°K have been measured, at a crystal temperature of 4.2°K, by perturbing the Boltzmann distribution in a multi-level spin system. Details of the experimental arrangement will be given with the results obtained.

author

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*This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

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Introduction

Shimoda[1] has suggested the use of masers in microwave spectroscopy, and Chang[2] has used traveling wave masers in the study of paramagnetic relaxation. The present paper describes the application of traveling wave masers to the direct measurement of changes in spin temperature in ruby for various perturbations. A particularly interesting phenomenon which may be observed is that of spin refrigeration[3] wherein the spin temperature may be lowered by application of microwave power at certain appropriate frequencies.

The technique employed is unique in that the thermal noise power

$$P_N = kT_sB \qquad (1)$$

where k = Boltzmann's constant,
T_s = spin temperature,
and B = bandwidth,

due to the spin system is measured directly. This direct method of measuring T_s has advantages over the usual method of measuring the attenuation of a signal propagated through the sample and subsequent computation of T_s from said attenuation, $a(T_s)$.

Sensitivity Threshold

For the sake of conciseness we analyze only the simple configuration shown in Fig. 1.

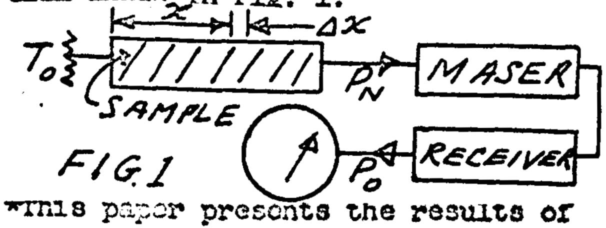

FIG.1

At any point $(x + \Delta x)$ in the test waveguide the noise power changes by[4]

$$\Delta p = -pa_s\Delta x + kT_sa_sB\Delta x \qquad (2)$$

where
a_s = attenuation constant due to the spin system at temperature T_s.
and $p = p(x)$ is the power at x.

It is assumed that the waveguide losses are very small compared with the paramagnetic absorption. Integration of Eq. 2 with appropriate boundary conditions, yields:

$$p_N = kT_oBe^{-a_sL} + kTB\left(1-e^{-a_sL}\right) \qquad (3)$$

The total noise power output which is read on the output meter is

$$p_o = p_NG + kT_MBG + kT_RBG \qquad (4)$$

where
G = total system power gain
T_M = noise temp of maser
T_R = noise temp of receiver referred to maser input.

The output meter will show fluctuations of the order of

$$p_o = p_o/\sqrt{Bt} \qquad (5)$$

where
B = predetection bandwidth
t = post detection time constant

Hence, the smallest change in spin temperature that may be detected is given by

$$\Delta T_s = \frac{T_s(1-g) + T_og + T_M + T_R}{(1-g)\sqrt{Bt}} \qquad (6)$$

where $g = e^{-a_sL}$.

For a typical maser system the numerator in (6) may be kept to 50°K or less, $t \simeq 1$ second, and $B \simeq 1$ Mc/sec (conservatively). Or

$$\Delta T_s \simeq .05°K \qquad (7)$$

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Spin Temperature

In a multilevel spin system the population of each spin state is given by the Boltzmann distribution law:

$$(n_i/n_j) = e^{-\frac{(E_i - E_j)}{kT}} \qquad (8)$$

where

n_i = number of spins in the i^{th} state

E_i = energy of i^{th} level, etc.

k = Boltzmann's constant

and T = temperature of the system

Conversely, it is possible to define a spin temperature, T_s, in terms of the occupation numbers n_i and n_j; thus,

$$T_s = \frac{E_i - E_j}{k\log(n_i/n_j)} \qquad (9)$$

Remembering that the total number of spins is conserved, it is readily seen that disturbance of any level will result in a redistribution of spins over all states; i.e., T_s corresponding to levels i and j may be perturbed by disturbing the m^{th} level, etc. Specific examples are given with experimental details in the next section.

Experimental Results

The experiment was performed with two S-band (2,400 Mc/s) traveling wave masers (TWM's) in the configuration of Fig. 2. One of the TWM's was used as a passive device and its input was terminated by a load at 4.2°K. The X-band waveguide normally used for pump power was used to perturb the ruby at frequencies other than the pump frequency.

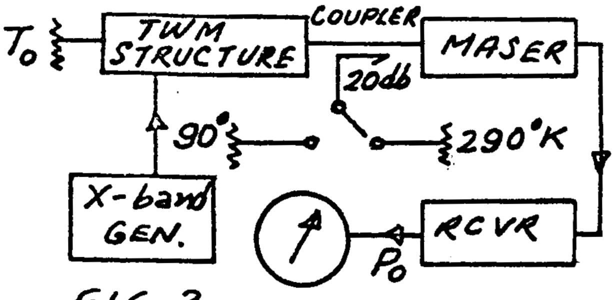

FIG. 2

The 20 db directional coupler and the two loads at 90°K and 290°K, respectively, permitted calibration of the system.

The specific result obtained may be explained in terms of the energy level diagram shown below:

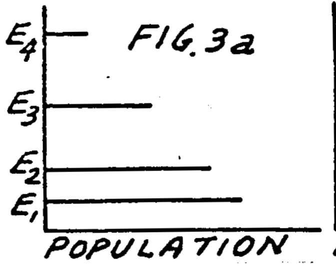

FIG. 3a

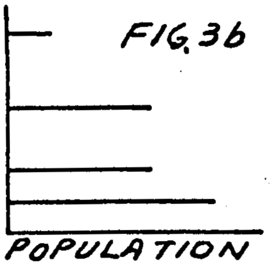

FIG. 3b

The transitions at $f_s = (E_2 - E_1)/h$ were observed while "pumping" at $f_{2,3} = (E_3 - E_2)/h$. Hence, the relative population distribution changed from that shown in Fig. 3a to that of Fig. 3b. The result is that the ruby sample appears to be colder at the transition frequency f_s. In like manner power at $f_{3,4} = (E_4 - E_3)/h$ showed that the spin temperature could be raised, which shows the relative transition rates. The changes in temperature observed were of the order of 1°K.

Conclusions

The effect of other perturbations on the spin - Hamiltonian of solids may be studied by the method outlined here. The effect of strong electric fields on the zero-field splitting constant in ruby will be investigated.

Acknowledgment

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