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MEASUREMENT OF THE CHROMIUM-DOPED RUTILE  
MASER OPERATING AT THE LIQUID NITROGEN  
TEMPERATURE

By

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## ABSTRACT

At the liquid nitrogen temperature, the profile of the inversion ratio was measured with various concentrations of chromium in rutile. Applying the effect of cross relaxation, as the result of observations, the inversion ratio of about 2 was obtained. At this temperature, we found that the maser action is possible, and the cross relaxation effect was observed in our rutile maser.

## 1. Introduction

The authors have already made some experiments on a chromium doped rutile maser operating at the liquid helium temperature. As the continuation of the last experiment, they have tried the measurement of the inversion ratio in the maser operating at the liquid nitrogen temperature to realize the practical maser which uses 2 Gc/s as the signal frequency and have obtained some useful data.

We discuss here about the relations of  $\text{Cr}^{3+}$  concentration vs. inversion ratio and pumping power vs. inversion ratio at the liquid nitrogen temperature.

## 2. Theoretical Consideration of the Maser Action

In both cases of the liquid nitrogen temperature and the liquid helium temperature, in order to obtain the large voltage gain-bandwidth  $\sqrt{G} B$  we must find the  $\text{Cr}^{3+}$  concentration which produces the most efficient maser action.

In the case of the reflection type maser with a single cavity, and when the voltage gain is high, the voltage gain-bandwidth is represented as follows:

$$\sqrt{GB} \approx \frac{2\nu_s}{|Q_m|} \approx \frac{2\nu_s}{Q_e}$$

and

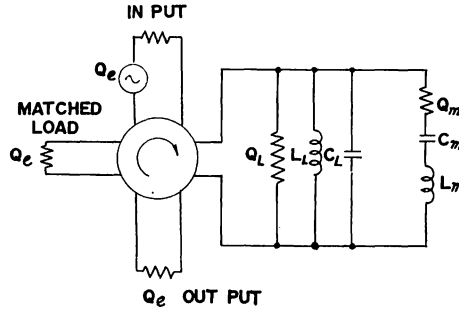


Fig. 1. Equivalent circuit of the reflection-type single cavity maser.

$$\frac{1}{Q_m} = \frac{P_m}{2\pi\nu_s E} = -\frac{h}{2\pi E} (n_3 - n_4) W_{34}$$

$$\therefore \sqrt{GB} \approx 2\nu_s \left( \frac{h}{2\pi E} \right) (n_3 - n_4) W_{34}$$

The inversion ratio can be calculated from the rate equations, and it is expressed as follows:

$$I \text{ (inversion ratio)} \equiv \frac{\Delta n_{34}}{\Delta_0 n_{34}} = -1 - \frac{\nu_p}{\nu_s} \frac{2w_l + w_c}{4w_l + w_c}$$

We use the above result and get the following result:

$$\sqrt{GB} \approx 2\nu_s \left( -\frac{h}{2\pi E} \right) I \Delta_0 n_{34} W_{34}$$

where

- $\nu_s$  = signal frequency ( $\nu_{33}$ ),
- $\nu_p$  = pumping frequency ( $\nu_{24}$ ),
- $Q_m$  = complex magnetic  $Q$ ,
- $Q_e$  = external  $Q$ ,
- $P_m$  = the power which is absorbed or radiated with the paramagnetic resonance of the maser material,
- $E$  = stored energy in cavity,
- $W_{34}$  = induced transition probability,
- $\Delta_0 n_{34}$  = difference in the spin population between state 3 and 4 at the thermal equilibrium, ( $n_3 - n_4$ ),
- $\Delta n_{34} = (n_3 - n_4)$ , when the pumping power is added,
- $w_l = w_{lj}$  spin-lattice relaxation probability,
- $w_c$  = cross relaxation rate.

Hence, in order to get large  $\sqrt{GB}$ , we must get small  $Q_e$  and small  $Q_m$ , too. In other words, these results indicate that we should make the inversion ratio

as large as possible. In addition, we must make  $\Delta_0 n_{34}$  larger. The liquid helium temperature maser is superior to the liquid nitrogen temperature maser as a large value of  $\Delta_0 n_{34}$  can be obtained. However, liquid nitrogen is economical and easy to handle, so the liquid nitrogen maser is more convenient for practical operation. If we utilize the cross relaxation effect and use a large ratio of  $\nu_p/\nu_s$ , we will be able to approach the characteristics similar to the liquid helium temperature maser. Then, the inversion ratio is an important factor in the maser actions. From this point of view, we made experiments mainly on the inversion ratio of the maser.

### 3. Experimental procedure

As the maser material, we made use of the crystal to be used in the liquid helium temperature maser. The rutile crystals doped with the chromium whose concentration was 0.05 wt %, 0.1 wt %, 0.15 wt % and 0.2 wt % were used in these experiments, and were cut in rectangle of  $4 \times 4 \times 4$  mm in the (110) and (001) directions.

The experimental signal frequency, pumping frequency and D.C. magnetic field are about 9.3 Gc/s, 35.6 Gc/s and 3.4 K gauss, respectively. The orientation of D.C. magnetic field is directed to  $70 \sim 80$  deg. from the C-axis. The structure of the cavity used is shown schematically in Fig. 2. Fig. 3 shows the microwave circuit diagram used.

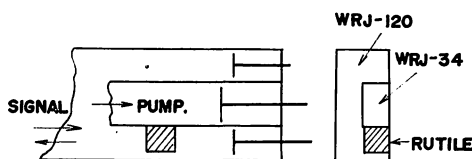


Fig. 2. Schematic diagram of the structure for observing the maser effect.

In the liquid nitrogen maser, the most difficult point is the method of refrigerating the maser material, because, if we insert the maser circuit directly into liquid nitrogen, microwave reflexion takes place at the liquid surface and fluctuates owing to its ceaseless motion. The observations of maser action are influenced by this fluctuation of reflexion. So we can not adopt the direct cooling of the maser material. We adopted the indirect method of refrigeration in which the maser circuit is inserted into a good thermal conductive pipe immersed in liquid nitrogen.

So the temperature of maser material depends on its pumping power dissipation, and the shift of resonance frequency of the cavity at the signal frequency occurs in the liquid nitrogen maser which needs high power pumping. The klystron, 2K25, as the source of signal frequency is controlled by powerful A.F.C. to follow the shift of resonance frequency of the cavity. We found that this maser material is too small to make use of this case, because the dielectric constant of rutile crystals at the liquid nitrogen temperature is less than that at

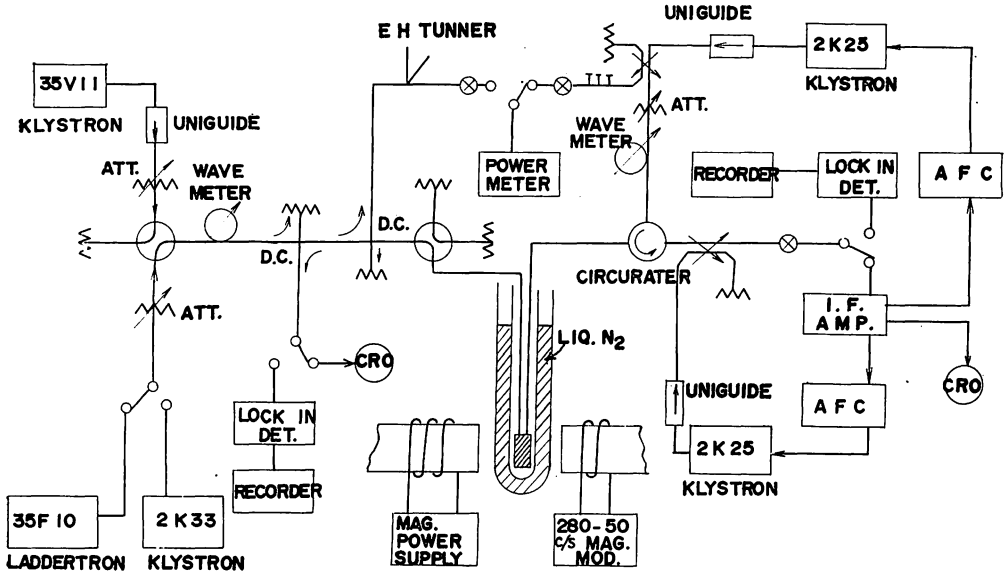


Fig. 3. Block diagram of the maser measuring system.

the liquid helium temperature. Therefore, the number of higher modes of resonance is less than at the liquid helium temperature. As the number of microwave resonances in the crystal in 9 Gc/s band is small, the number of desired resonance points can not be selected freely. This situation is disadvantageous for adjustment of the condition of the cross relaxation effect. We consider that this problem will be solved by application of larger maser material than that in the liquid helium maser.

#### 4. Experimental Results

Fig. 4 represents the experimental result of the relation of inversion ratio

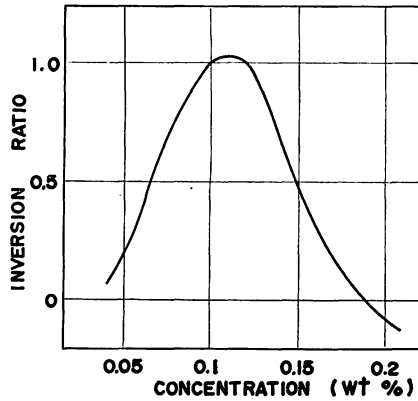


Fig. 4. Concentration-Inversion ratio.

vs. concentration. This result shows that the largest inversion ratio is obtained at the concentration of 0.1 wt %.

As the result of measurement, the rutile crystal doped with 0.1 wt % of chromium concentration is most useful as a liquid nitrogen maser material as well as a liquid helium temperature maser, and here attention must be given to the fact that the signal power must be less than  $-60$  dBm at which the effect of saturation is negligible. By application of the effect of cross relaxation, the inversion ratio of about 2 is obtained in the case of concentration with 0.05 wt %. The results of estimation of the inversion ratio as a function of pumping power are shown in Fig. 5 in the cases of the liquid helium temperature and the liquid nitrogen temperature. The inversion ratios are compared in the cases with and without cross relaxation effect.

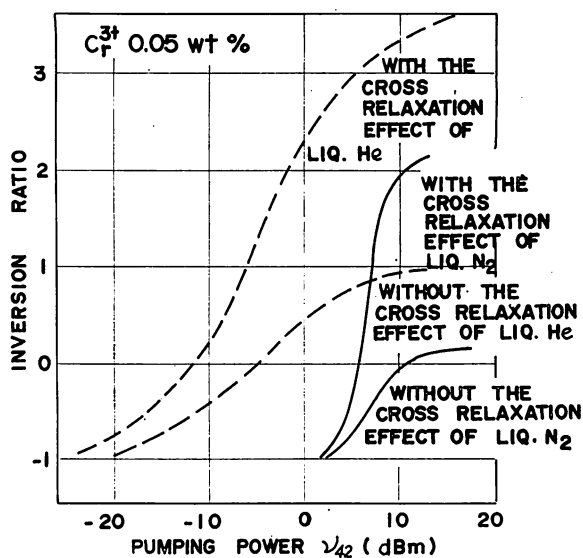


Fig. 5. Pumping power-Inversion ratio.

These results indicate that the maser operating at the liquid nitrogen temperature requires higher pumping power than the liquid helium temperature maser. As the pumping power increases, the inversion ratio becomes larger rapidly, and in the case of the normal maser, in spite of high pumping power, the inversion ratio can not be larger than about 0.2. Generally speaking, the variation of inversion ratio as a function of the pumping power takes place more rapidly than at the liquid helium temperature. Also, the maser actions are observed only at the high pumping power level. In the present situation, it has not yet been improved sufficiently against the influence of temperature variation in maser material. Therefore, we could not approach the value of the theoretical inversion ratio. Further examinations are required on these points.

### 5. Conclusion

There were made clear of some properties of the inversion ratio in  $\text{Cr}^{3+}$  doped rutile at the liquid nitrogen temperature. Making use of the cross relaxation effect at the liquid nitrogen temperature, we will be able to approach to some extent to the case of the liquid helium temperature maser.

As the inversion ratio is decided with the ratio of  $\nu_p/\nu_s$ , if we adopt  $\nu_p=40$  Gc/s and  $\nu_s=2$  Gc/s, better results will be obtained. If the pumping power of about 10 dBm is supplied, the maser action is possible at the liquid nitrogen temperature, and as the result, there is a good prospect of realizing the liquid nitrogen temperature maser.

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