MILLIMETER- AND SUBMILLIMETER-WAVE DETECTION BY PARAMAGNETIC MATERIALS*

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INTRODUCTION

Due to a lack of powerful signal sources in the millimeter- and submillimeter-wavelength range, a sensitive detector is an essential requirement for work in this frequency band. Adaptations of microwave and optical devices to this wavelength region have many limitations. One means of circumventing the problems associated with operation in this region is to convert the short wavelength radiation to lower frequencies where low noise detection techniques are available.[1-4] This paper describes the theoretical and experimental evaluation of a downconverter which utilizes paramagnetic materials. Using materials with appropriate zero field splittings this device should be operable over the millimeter- through far-infrared-wavelength range.

DOWNCONVERTER OPERATION

The paramagnetic downconverter is essentially a frequency converter which transfers the information on the millimeter-wave signal to a microwave signal. An energy-level diagram appropriate for the operation of this device is shown in Fig. 1. When a millimeter-wave signal of frequency ν_{13} is incident, the population of level 3 will be increased and that of level 1 will be decreased. Under ideal conditions, the extra electrons in level 3 will relax to level 2 thereby increasing its population. A microwave signal of frequency ν_{12} can detect this change in population. Therefore the information on the millimeter-wave signal is now superimposed on the microwave signal. Using a low noise receiver at the microwave frequency, sensitive detection of the millimeter-wave signal can be achieved.

* This work was supported by the National Aeronautics and Space Administration under Grant No. NGL 23-005-183.

NOTES

CONVERSION LOSS

The conversion loss is an important parameter in the operation of any frequency translation device. The rate equations[5] can be used to estimate the conversion loss expected in the paramagnetic downconverter. These equations describe the response of the level populations to thermal relaxation and external excitation processes.

The time dependence of the ith level population is given by the equation

$$\frac{dn_i}{dt} = \sum_{j=1}^{3} [-(\omega_{ij} + W_{ij})n_i + (\omega_{ji} + W_{ji})n_j] \quad , \qquad (1)$$

where n_i = the population of level i,

ω_{ij} = the thermal relaxation rate from level i to level j and

W_{ij} = the stimulated transition rate from level i to level j.

The solution of these equations for small W_{13} shows that

$$n_1 - n_2 \cong \frac{(n_1 - n_2)^{\circ} - T_{13}W_{13}}{1 + T_{12}W_{12}} \quad . \qquad (2)$$

Here T_{12} and T_{13} are relaxation times related to the ω_{ij} terms.

The power absorbed at ν_{12} is

$$P_{12} = h\nu_{12}(n_1 - n_2)W_{12} \quad , \qquad (3)$$

where h is Planck's constant. Thus the decrease in power absorption ΔP_{12} due to the presence of the millimeter-wave signal is

$$\Delta P_{12} = -\frac{h\nu_{12}T_{13}W_{13}W_{12}}{1 + T_{12}W_{12}} \quad . \qquad (4)$$

Therefore the general form for this equation can be written in the form

$$\Delta P_{12} = \frac{LP_{mm}P^{i}_{12}}{1 + P^{i}_{12}/P^{i}_{sat}} \quad , \qquad (5)$$

where P_{mm} = the millimeter-wave power level,

P^i_{12} = the incident power at ν_{12},

P^i_{sat} = the saturation input power at ν_{12} and

L = a constant.

In this case the downconversion loss is

$$L_{dc} = \frac{1 + P^i_{12}/P^i_{sat}}{LP^i_{12}} \quad . \tag{6}$$

NOISE SOURCES

There are three main sources of noise in this device. First, amplitude and frequency fluctuations in the local oscillator will appear as amplitude fluctuations in the microwave output. Second, the microwave frequency transition has an equivalent noise temperature. This temperature will increase as the local oscillator power level increases since the level populations will tend to be equalized thereby increasing their apparent noise temperature. Finally, the noise figure of the following amplifier must be accounted for in determining the minimum detectable power for the downconverter.

In the downconverter, the changes in power absorption at the microwave frequency are determined by monitoring the power reflected by the device. Since the millimeter-wave power causes small changes in the microwave power level, the detection problem is one of determining small changes in a relatively large power level. In this situation the smallest observable change in power is[6]

$$\Delta P_{12} = 2\sqrt{P_n P^o_{12}} \quad , \tag{7}$$

where P_n is the noise power at the device output as determined by the three sources above and P^o_{12} is the microwave power level at the output terminal. Combining Eqs. 6 and 7 and optimizing with respect to P^i_{12} shows that

$$(P_{mm})_{min} = \frac{4\sqrt{P_n P^o_{12}}}{LP^i_{sat}} \quad . \tag{8}$$

If the downconverter and local oscillator do not contribute significantly to P_n, then

$$(P_{mm})_{min} = \frac{4\sqrt{F_A kTBP^o_{12}}}{LP^i_{sat}} , \qquad (9)$$

where F_A = the following amplifier noise figure and

B = the following amplifier bandwidth.

In Fig. 2 the values of $(P_{mm})_{min}$ and $(NEP)_{mm}$ (B = 1 Hz) are tabulated for liquid nitrogen and liquid helium operation. These calculations assume reasonable operating parameters for the downconverter and optimized external circuit. Preliminary measurements on a nonoptimum external circuit tend to confirm the theoretical predictions.

EXPERIMENTAL RESULTS

An experimental model of the device described above has been built and operated successfully at 4°K and 77°K. In these experiments input frequencies were in the 35 to 60 GHz range so that an accurate evaluation of the device characteristics could be made. The microwave output frequency in these experiments was about .9 GHz. Figure 3 shows the energy level diagram for one operating point. Figures 4 and 5 are experimental results of some liquid nitrogen temperature measurements at this operating point. Figure 6 shows the input and output signals of the downconverter. Further work is underway to evaluate the response time and minimum detectable power for this device.

CONCLUSIONS

The feasibility of operating a downconverter as described above has been demonstrated. It is felt that the initial results warrant further investigations especially with input frequencies above 100 GHz where sensitive detectors are not readily available.

LIST OF REFERENCES

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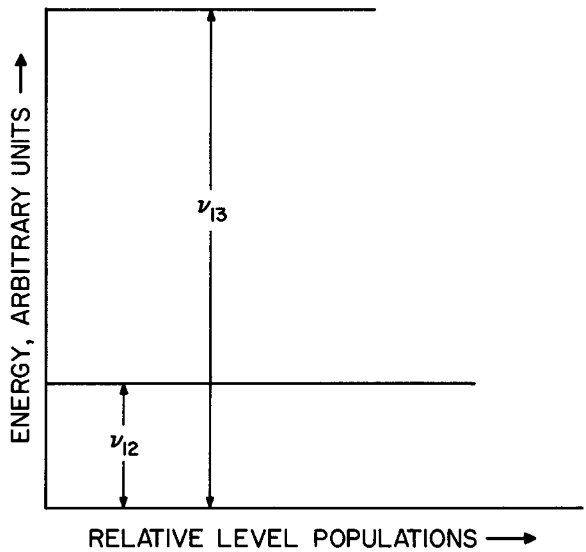

FIG. 1 ENERGY LEVELS SUITABLE FOR PARAMAGNETIC DOWNCONVERTER OPERATION.

T_D	77°K	4°K
L	10	1000
P^i_{sat}	2.5 mW	25 μW
P^o_{12}	2.5 nW	25 pW
F_A	4	4
B	1 MHz	1 MHz
T	290°K	290°K
$(P_{mm})_{min}$	$5\cdot10^{-11}$ W	$1.6\cdot10^{-13}$ W
NEP_{mm}	$5\cdot10^{-14}$ W	$1.6\cdot10^{-16}$ W

FIG. 2 DOWNCONVERTER MINIMUM DETECTABLE POWER.

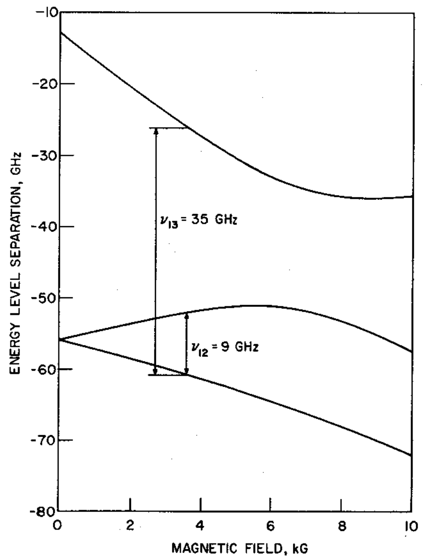

FIG. 3 ENERGY VS. FIELD DIAGRAM FOR DOWNCONVERSION FROM 35 GHz TO 9 GHz.

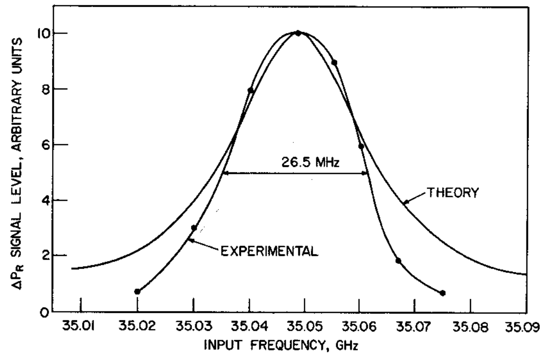

FIG. 4 INPUT RESPONSE OF DOWNCONVERTER.

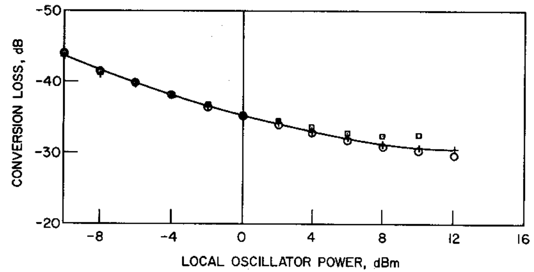

FIG. 5 DOWNCONVERTER OVERALL CONVERSION LOSS (LINE AND MISMATCH LOSSES = 8.3 dB).

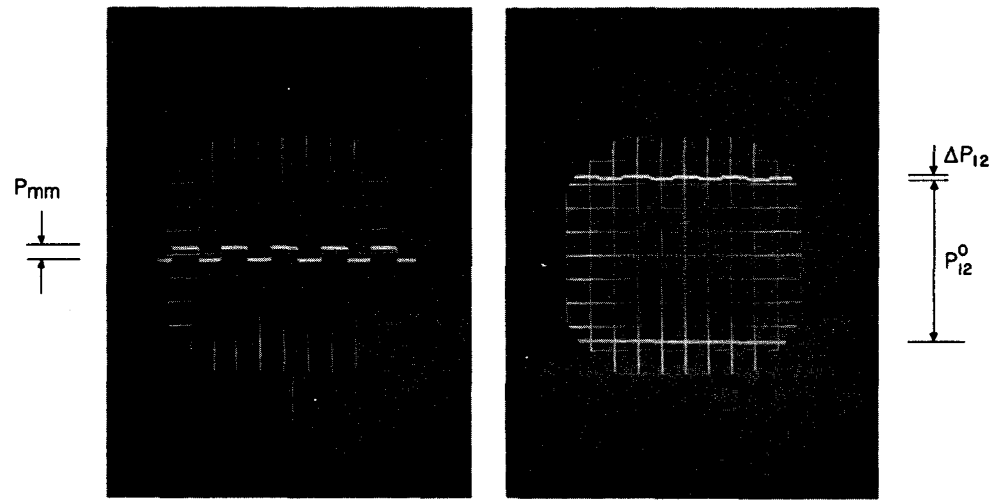

FIG. 6 INPUT AND OUTPUT SIGNALS FROM DOWNCONVERTER.