the desired wavelength was placed in tandem so that the zero-order reflection (the only one existing for the desired wavelength) reached the detector. Submultiples of this wavelength, which would normally also be transmitted through the spectrometer, were now diverted into other orders with the usual high efficiency of the echelette grating. It was possible, therefore, to make measurements at, say, the 10th harmonic without serious interference from the 20th harmonic.

The over-all insertion loss of the spectrometer ranged from 5 to 3 db and from 5.4 to 1.0 mm, mainly due to horn and waveguide losses. This instrument proved to be very convenient for harmonic identification and separation, and certainly could not be replaced by conventional types of microwave wavemeters at these wavelengths.

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Submillimeter Photon Counting in Ruby*

A microwave detection process very similar to Bloembergen's quantum counting[1] has been observed in the vicinity of 500 Gc using the fluorescence of ion pairs in red ruby. The detector which has been realized is quite sensitive and particularly simple because it uses polychromatic light for pumping. The results reported here are preliminary, and the apparatus is not refined for detection beyond the stage at which feasibility has been shown.

The quantum systems responsible for submillimeter photon counting are the ion pairs which exist in significant numbers in red ruby. The fourth neighbors and those closer have a large spin-exchange interaction which modifies the pair spectra in such a way that the ground state of the Cr^{+++} pair is split into four energy levels of total spin 3, 2, 1 and 0 since each ion has a spin of 3/2.[2] The transition frequencies among the spin levels of the fourth and second neighbor pairs are in the range of 300 to 3000 Gc.[3]

An approximate energy level diagram of the fourth neighbor pairs is shown in Fig. 1, and on it is the simplified photon counting cycle. This cycle does not depend upon the use of monochromatic pumping light to sense changes in the populations of the ground state levels; instead it utilizes the indigenous selection rules in the normal fluorescence cycle of the red ruby crystal. This is evident in the following description of the counting cycle:

1) In a ruby crystal at 4.2°K, only the lowest energy level of the pair system ($S=3$) is significantly occupied. If it is assumed that the intensities of transitions from this level to the U band are relatively low, when the crystal is pumped with green light the resulting fluorescence from the fourth neighbor pairs is small.
2) When a microwave signal at the proper frequency (615 Gc) is incident on the crystal, there will be absorption, and this will cause an increase in the population of the $S=2$ level.
3) If the $S=2$ level has a strong transition to the U band, the increase in its population will cause an increase in the total fluorescence from the crystal.

Monitoring the fluorescence from the crystal completes the photon counting detection scheme.

One factor, perhaps a critical factor, has been neglected in the preceding discussion; nonradiative energy transfer from isolated ions to pairs makes a major contribution to the fluorescence, and it is very likely that this transfer is sharply frequency selective, particularly at low temperatures. With the information available, it is impossible to discriminate between effects due to this transfer and the simpler effects discussed above.

The apparatus which was used to observe detection is shown in Fig. 2. All the active elements are placed within the insulating space of a specially constructed helium cryostat. The ruby crystal, about 0.3 mm³ of dark ruby, is cooled by conduction through the copper bottom of the helium vessel. This copper plane also acts as one end of the bisected-confocal microwave cavity; the other end is an evaporated silver coating on the polystyrene lens. The lens end is tunable, by means of a micrometer and lever system, over a 2 mm range about the mean cavity length of 1 cm. Pumping light enters the cryostat assembly vertically through a fused quartz window, and, after being deflected by the front surface mirror, it reaches the ruby at a 45° angle. The fluorescence is detected by a commercial thin-film Ge bolometer, and the radiation reaching it is limited by a sharp cutoff red filter, which passes wavelengths greater than 6500 A.

The pumping light source is a 500 watt, Hg-Xe compact arc lamp, and the arc is imaged on the ruby by an $f/2.5$ lens. The light is mechanically chopped at 50 cps to allow the use of a lock-in amplifier.

The microwave signal is thermal radiation, and it enters the cavity by means of

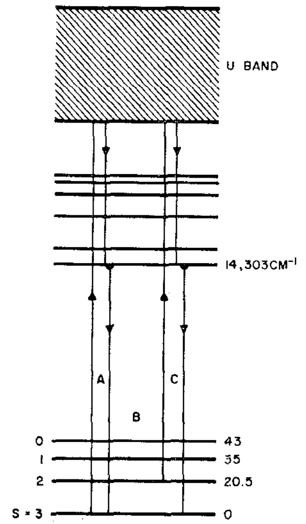

Fig. 1—Partial energy level diagram (from Kisliuk, Schawlow, Sturge[3]) of the fourth neighbor pairs of Cr^{+++} in ruby, showing the simplified photon-counting cycle.

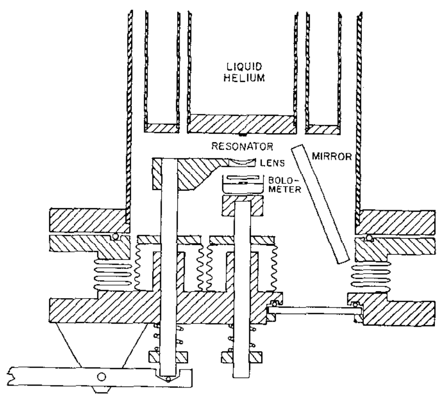

Fig. 2—A cross-section view of the basic assembly used to observe the submillimeter detection.

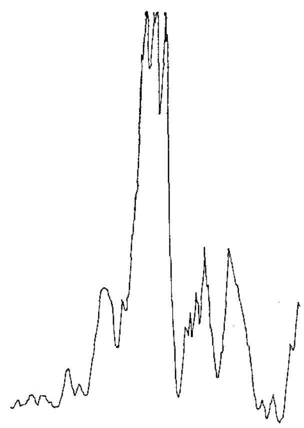

Fig. 3—A recorder trace of the bolometer output as the cavity frequency passes through the 612 Gc ruby resonance. The principal peak is 480 Mc wide.

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[1] N. Bloembergen, "Solid state infrared quantum counters," *Phys. Rev. Lett.*, vol. 2, pp. 84–85; February 1959.

[2] A. L. Schawlow, D. L. Wood, and A. M. Clogston, "Electronic spectra of exchange-coupled ion pairs in crystals," *Phys. Rev. Lett.*, vol. 3, pp. 271–273; September, 1959.

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the losses of the movable end of the cavity, which is at room temperature. Because the microwave thermal energy is concentrated in the modes of the cavity, its frequency distribution is sharply peaked at the resonant frequencies of the cavity.

Experimentally, the detection has been observed by tuning the cavity through its range, and, whenever the frequency of the cavity is coincident with one of the detecting frequencies, the fluorescence exhibits a pronounced increase. Fig. 3 illustrates a typical response as a pair resonance is scanned. The frequency detected may be inferred from measurements of the intervals between related resonances. In the experiments, several frequencies representing activity by both the second and fourth neighbor pairs were observed. Of these, the two frequencies that have been measured most accurately are due to the fourth neighbors; these responses occurred at 612 Gc ± 3 Gc (20.4 ± 0.1 cm^{-1}) and 426 Gc± 6 Gc (14.2 ± 0.2 cm^{-1}). These two lines had apparent widths of approximately 500 Mc.

At 4.2°K, tuning a cavity resonance through one of the frequencies above caused an increase of 20 per cent in the total fluorescence picked up by the bolometer; this represents a power change of roughly 5×10^{-8} watts. Because of the nature of the microwave power source, it is very difficult to estimate the power input to the detector. Taking account of the loss of the silver coating, and the multiplicity of modes contributing to the excitation, a probable upper bound to the power input to the ruby is 10^{-10} watts. Within the limitations of this estimate, the net up-conversion gain is 500. The frequency ratio of the output to input signals is in the range of 700:1000.

There has been no measurement of the time constant of this detector, though it is assumed that the detection time constant is about the same as another unmeasured quantity, the spin-lattice relaxation time. The fact that the detector does operate suggests that the spin-lattice relaxation time is rather long, very likely too long for communications applications. One may anticipate, however, the possibility of using such a detector, located in a totally cooled resonator, as a submillimeter radiometer.

Perhaps more important than the direct detection potentialities of the system that has been studied, is the evidence this experiment provides for the existence of an absorption involving the $\Delta S = 1$ transitions by the Cr-ion pairs in ruby; this effect is denied by simple isotropic spin-exchange. Its existence opens the way to other quantum electronics systems in the submillimeter region using this readily avilable material.

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A Measurement of Bolometer Mount Efficiency at Millimeter Wavelengths*

Introduction

In recent studies of a pulsed source of millimeter and submillimeter waves[1] the average power of the signals generated was below the sensitivity of common power meters that utilize barretters or thermistors. A device was required that measured peak power or energy per pulse.

A method for measurement of peak power employing bolometers had been developed for power levels of a few milliwatts in the centimeter wavelength range (up to *K* band).[2] In this method the nearly linear resistance rise of a barretter upon application of a RF rectangular pulse is differentiated. The differentiation produces a step function, and a peak reading instrument measures its amplitude.

This method was adapted to measure peak power in the order of tens of microwatts in the millimeter and submillimeter range. A simple RG-99 waveguide mount was built to hold a commercial bolometer element normally used in RG-98 waveguide. The bolometer (nominally 200 Ω) was connected to a 6-v battery through a 1000-Ω resistor. The transient changes of the voltage across the bolometer were observed on an oscilloscope through an ac-coupled amplifier. Since the observed changes were generally less than one per cent of the total bias voltage on the bolometer, the arrangement gave an essentially constant-current supply.

In use, the microwave pulse caused the temperature of the barretter to increase. The thermal time constant was much shorter than the inter-pulse period, so that the temperature would fall off to the initial value before the next pulse arrived. This change in temperature was accompanied by a change in resistance. The circuit described above provided a video pulse with an amplitude proportional to the change in resistance. It is readily shown that the area under the video pulse represents the total microwave energy absorbed and that the peak power of a rectangular pulse is proportional to the amplitude of the video pulse ΔV, and is given by

$$p = \frac{\tau}{\Delta t} \frac{(R + r_0)^2}{R} \frac{\Delta V}{E \frac{dr}{dp}},$$

where τ is the thermal time constant of the bolometer, Δt is the length of the rectangular pulse, E is the bias voltage, R and r_0 are the bias and barretter resistances, respectively, and ΔV is the peak value of the video pulse. The rate of change of barretter resistance with power was calibrated at dc. The calibration sensitivity obtained was one millivolt per milliwatt-microsecond.

Measurement of Mount Efficiency

The bolometer, although mounted in waveguide, was generally used for measurements in a quasi-plane-wave setup such as shown in Fig. 1. It was essential, therefore, to determine how much of the power incident on the parabola was actually absorbed in the bolometer wire itself. A measurement of "mount efficiency" was therefore made in which the parabola, horn and connecting waveguide were all considered part of the mount itself.

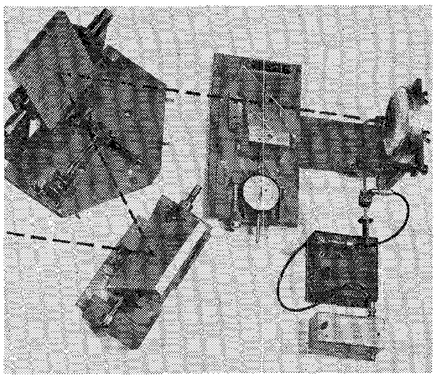

Fig. 1—Experimental arrangement.

The experimental arrangement was similar to that of Fig. 1. The apparatus is shown in the configuration used to calibrate the coupling coefficient of the diagonal, dielectric slab used as a directional coupler. The coupling was determined directly from a measurement of the *Q* and the coupling coefficient of the parallel-plate resonator shown. The detector was then moved to replace the upper plane mirror, and the laboratory itself was found to be a satisfactory termination for the straight-through arm of the coupler.

The impedance of the detector was measured[3] for various values of bolometer resistance and plotted on a Smith Chart. From the extrapolated values of impedance for zero and infinite bolometer resistance, the mount efficiency was readily obtained. The extrapolation was facilitated by utilizing the tuning stub on the bolometer mount. For each value of bolometer resistance, an impedance circle was plotted as the tuner was adjusted. The circles were tangent at a common point which was taken to be on the zero-resistance circle for the bolometer. The points of maximum sensitivity on each circle defined another circle (the transformed "resistive axis" of the bolometer itself) orthogonal to the family of experimental circles. This provided adequate data to average out experimental errors. The mount efficiency was then computed by a method analogous to that of Kerns.[4]

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