A GERMANIUM BOLOMETER FOR THE FAR INFRARED

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by

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SCOPE AND CONTENTS:

A technique has been developed for constructing low temperature germanium bolometers for use as detectors in the far infrared. Their performance has been evaluated both by measuring their responsivity and noise and comparing these with the theoretical values and also by using the bolometer in conjunction with a far infrared spectrophotometer to obtain spectra showing the theoretical resolution of 0.11 cm^{-1} at 55 cm^{-1} expected for this instrument.

ACKNOWLEDGEMENTS

I should like to express my thanks to my research director, Dr. T. Timusk, for his invaluable advice, assistance and encouragement at all stages of this work and to Dr. J. Shewchun for many helpful discussions and for the use of both equipment and facilities for preparing the samples.

I should also like to acknowledge Dr. S. Zwerdling of M.I.T. for his suggestions on the sources of materials.

The optical system used with the bolometer in conjunction with the interferometer was constructed by Mr. R. Ward and I should also like to thank him for preparing the interferometer and for producing the spectra shown in Figs. 15 and 16.

I should like to thank Dr. W. R. Datars and Dr. C. V. Stager for their cooperation in lending equipment and to Miss Sybille Schonfeld and Mrs. Helen Kennelly for typing the manuscript.

Finally, my wife Trudie, for her support in my hour of need.

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INTRODUCTION

There has been an increasing interest in the use of the low-temperature germanium bolometer as a detector in the far-infrared following the work of Low[1]. Only a very small fraction of the total radiation from sources of infrared is emitted in the far infrared region and as the energy associated with these wavelengths is small, the basic requirements of any detector intended for use in the far infrared are that it be very sensitive and that it possess very little noise. The work of Low showed that the germanium bolometer could fulfil these requirements.

The bolometer is a thermal detector and so unlike the photon detectors it responds to all wavelengths of incident radiation. The radiation absorbed by the bolometer causes an increase in temperature resulting in a change of resistance which may be used as a measure of the incident radiation. At low temperatures, germanium has a low thermal capacity, a high thermal conductance and as it is a semiconductor it has intrinsically a very high resistivity and temperature coefficient of resistance. Consequently the cooled germanium bolometer is inherently a very sensitive detector and may be shown to have the best theoretical performance particularly when a detector of large area is required.

This report describes in detail a procedure for constructing, testing and optimizing the performance of a germanium bolometer. The research was carried out with a group concerned primarily in the infrared spectroscopy of solids and one of these detectors has been installed in a spectrophotometer system currently being used to investigate the absorption of various materials is the far-infrared. An overall signal-to-noise ratio greater than 1000:1 is obtained which permits the theoretical resolution of 0.07 cm^{-1} to be achieved at wavelengths greater than 100 cm^{-1}. At present this resolution is limited by the mechanical length of travel of the interferometer mirror and not the bolometer. A typical signal to noise ratio in the output, of the bolometer alone contributed to the noise, would be 10000:1.

THEORY

Responsivity

A theory of the germanium low-temperature bolometer has been given by Low[1]. Over the temperature range 1.1^oK to 4.2^oK the resistance of germanium is given approximately by

$$R(T) = R_o(T_o/T)^A \tag{1}$$

where R_o is the resistance at a temperature T_o and A is a constant which is approximately 4. Using (1) the temperature coefficient of resistance $\alpha(T)$ may be evaluated in terms of A:

$$\alpha(T) = (dR/dT)/R = -A/T \tag{2}$$

Assuming that radiation from the bolometer itself is negligible, the total energy dissipated in the bolometer is conducted to the heat sink. With no signal present, the equilibrium temperature T of the bolometer is given by

$$T = T_o + (P+Q)/G \tag{3}$$

where P = EI is the electrical power dissipated in the bolometer element, Q is the radiation power absorbed by the bolometer element and G is the thermal conductance of the leads from the element to the heat sink at temperature T_o.

For the proper operation of the bolometer $Q < P$. In our case, typically $Q = 0.05$ μW and $P = 5$μW.

Making the further assumption that G is a function of T_o but not of T and that the load resistance $R_L \gg R$, the responsivity S, which is defined as

$$S \equiv \Delta E/\Delta Q \qquad (4)$$

can be obtained from

$$\Delta E = I\Delta R = I\alpha R\Delta T$$

and as

$$Q = (T-T_o)\ G-P$$

the signal ΔQ is given by

$$\Delta Q = \Delta T\ G-I^2\Delta R = \Delta T(G-I^2R\alpha),$$

giving

$$S = I\alpha R\ /\ (G-\alpha P). \qquad (5)$$

Where R cannot be assumed very small compared with R_L, the responsivity S^* is given by

$$S^* = SR_L/(R_L+R) \qquad (6)$$

Sources of Noise

A figure of merit often used for detectors is the noise equivalent power (N.E.P.). This is the power that may be detected with a signal to noise ratio at the output of unity and is commonly referred to unit bandwidth. The sources of noise in a bolometer have been described by Low and Hoffman[2]. The square of the N.E.P. may be written as the sum of independent terms:

$$(\text{N.E.P.})^2 = 4kTR/S^2 + 4kT^2G + 8\varepsilon\sigma kAT^5 + 8\varepsilon\sigma kAT_b^5 \sin^2(\tfrac{\theta}{2}) + CI^\beta/f^\gamma S^2 \qquad (7)$$

where the first term is the contribution of the Johnson noise in the bolometer and the second is the temperature noise power due to the heat flow from the bolometer to the heat sink. Stefan's and Boltzmann's constants are σ and k respectively. The average emmissivity is ε. The third term represents the radiation from the element and the fourth corresponds to the noise associated with the radiation from a background at a temperature T_b accepted by the bolometer within an angle θ. Current and 1/f noise are contained in the last term. In a complete experimental arrangement the radiation noise of the source and also the noise of the amplifier should be considered.

Comparing the magnitudes of these terms for a bolometer at helium temperatures, the first two are similar and the third is so small that it can be neglected. If the bolometer performance is limited by the fourth term, it operates in a "background limited" condition. This condition is usually met when the bolometer is exposed to a hemispherical unfiltered radiation field. In this case the radiation noise dominates. This noise will be reduced if the angle of acceptance of the radiation is restricted and by the use of filters.

Cooled filters reduce the incident radiation by selectively absorbing unwanted wavelengths and not reradiating them. An ideal filter would transmit in a narrow band at the signal wavelength. Consequently there are two effects on the bolometer of using cooled filters. A low background power permits operation with a very high responsivity, i.e., with a low thermal conductance to the bath without an unduly high temperature of the element T. Secondly, it reduces the level of background radiation noise.

Selecting the Operating Point

Although the performance of a bolometer may be deduced in terms of its various parameters, once a bolometer has been made and installed in the system, its inherent properties cannot be changed. Further, the filters are determined by the spectral region of interest together with the absorption spectrum of the different materials available. The signal chopping frequency may also have been fixed by other considerations. The bias current which sets both the potential difference across the element and its equilibrium temperature can be adjusted and its optimum theoretical value can be calculated.

The bolometer time-constant may be shown[1] to be

$$\tau = c/(G - \alpha P) \qquad (8)$$

where c is the thermal capacity of the element of volume v given by[3]

$$c = 6.8\ T^3 v \quad \text{joules deg}^{-1}\ \text{K}$$

and τ is the rise-time of the output signal from the bolometer when a square-wave input is applied.

Assuming a value for α of $-4/T$, the thermal conductance of G may be evaluated using equation (8).

Note that if the variation of the resistance of the bolometer element with temperature is obtained, G may also be deduced from the static characteristic using the relation

$$G = P/(T-T_o) \qquad (9)$$

where T is read from the graph of R vs T. This method must be used with caution if diode characteristics are present, since it is very difficult to separate the effect of an increase in the resistivity of the bulk material from the temperature dependence of the diode characteristic. It is not possible to recognize this condition from the static characteristic alone if the two junctions are symmetrical, resulting in the same characteristic on reversing the polarity.

The low-frequency responsibity S is given[1] by

$$S = \alpha E/(G - \alpha P) \qquad (10)$$

and so the responsivity may be calculated for any point on the static characteristic. The maximum responsivity S_{max} given[1] by

$$S_{max} = -0.7 \ (R_o/T_oG)^{\frac{1}{2}} \qquad (11)$$

is obtained for A = 4 when

$$P = 0.1 \ T_oG \qquad (12)$$

This optimization is given by Low and neglecting current noise, it maximizes the responsivity. If the bolometer is limited by current noise a somewhat lower bias may be found to give a better signal to noise ratio. In our case with both the extreme filtering of the background radiation and the presence of excess current noise, the operating points have been determined empirically to maximize the signal to noise ratio.

Experimental Procedure

The system will be described in these principal sections: the optical system, the bolometer element and the electrical measurements.

The Optical System

Radiation enters the bolometer system through the optional entrance cone and passes through a black polyethylene seal into an elbow section where it is reflected from a plane polished surface down the vertical light pipe to the filter compartment immersed in liquid helium, Fig. 1. This contains a short condensing cone directly above the cavity containing the bolometer element. The two cones are intended to match the diameter of the incident radiation to that of the bolometer element. Elements of 0.125" and 0.25" diameter have been used. The light pipe is 0.43" I.D. brass tubing and the centre section was machined to a wall thickness of 0.008" to reduce thermal conduction to the liquid helium.

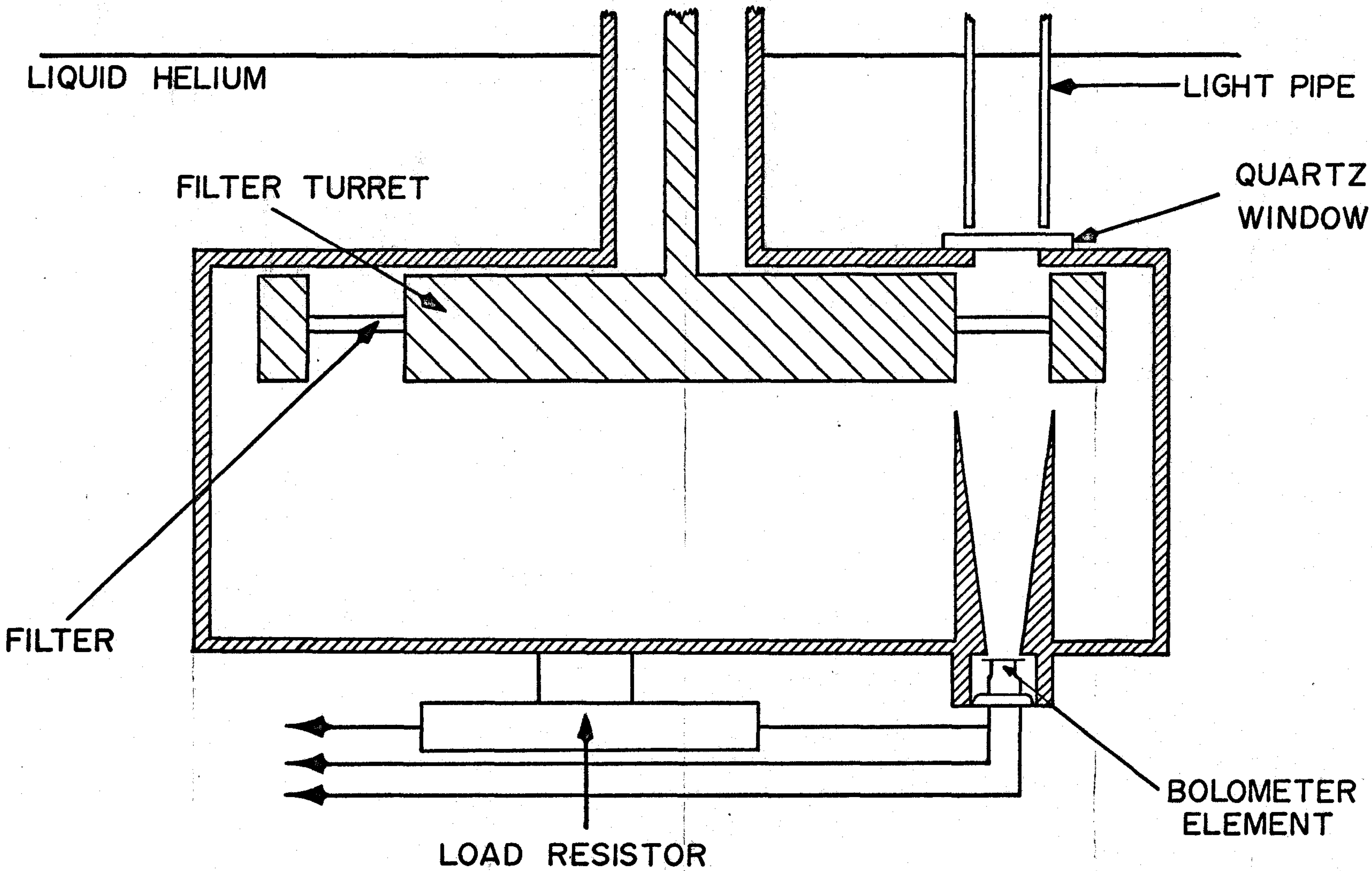
The detector has been designed so that it may be used with either an interferometer, the R.I.I.C. Fourier Spectrophotometer FS-720 or a Perkin-Elmer 301 spectrophotometer. At present it has been used only with the interferometer where the entrance cone is unnecessary as the emerging radiation is focused to a small image.

The evacuated sample compartment has a crystal quartz window covered with two layers of black polyethylene 0.0015" thick which absorb regions of the spectrum above

Fig. 1

The filter and bolometer compartment. This evacuated copper box contains a number of filters mounted in the turret which can be rotated from above and the bolometer element with its condensing cone.

FIG.1


LIQUID HELIUM
LIGHT PIPE
QUARTZ WINDOW
FILTER TURRET
FILTER
BOLOMETER ELEMENT
LOAD RESISTOR

300 cm^{-1}. It contains a rotor which carries the crystal filters whose absorption is being investigated. These are held firmly by springs and both the thrust washers and seals are well tinned with indium to ensure a good thermal contact and an even pressure to minimize strain.

It was initially hoped to use this system with a conventional helium storage dewar but this placed a restriction on the size of the filters making it inconvenient to mount them. The helium dewar used for this experimental work has an I.D. of 3.5". In principle it is possible to build a simple filter compartment to fit a storage dewar.

The Bolometer Element

This section describes a procedure for making a bolometer element and mounting it in the optical system.

a. Preparation of the Materials

The two crystals of gallium doped p-type germanium that have been used for making these elements are of resistivities 0.12 and 0.07 ohm. cm. They have been found suitable for use with helium bath temperatures of 4.2^{o}K and 2^{o}K respectively.

The single crystals were sliced and lapped to a thickness of 0.008" by the Semiconductor Specialties Corporation and cut into circular discs using an ultrasonic impact grinder in the McMaster Instrument Machine Workshop.

The discs were cleaned and then etched in a mixture of 20% glacial acetic acid, 20% hydrofluoric acid and 60% nitric acid, (C.P.-4), in an ultrasonic cleaner to a thickness of between 0.004 and 0.005 inches. This procedure ensures an even etching of the surface to below the level at which damage may have been caused by lapping. The etch was then flushed away with distilled water from a Barnstead Still, and the samples washed for four hours to remove the acid.

The 0.005 inch diameter gold wire* used for the electrical and thermal contacts had been doped with 1% gallium. This doping is intended to minimize the formation of p-n junctions at the crystal-wire interfaces. It was found, for example, that the use of wire doped with 1% indium produced very noisy junctions with diode properties. (Note that Ga and In are both acceptors.) It was found, however, that even with the 1% gallium doped wire there was evidence of diode characteristics. The gold wire was cut into lengths of 0.25", degreased with chloroform in the ultrasonic cleaner, rinsed with alcohol and kept under alcohol until required.

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* Sigmund Cohn Incorporated.

b. Alloying

The small general purpose alloying furnace illustrated in Figs. 2 and 3 was used to attach the gold wires to the germanium discs. It was fitted with a heating element of nichrome foil 0.003 inches thick and provides the temperature necessary for the alloying process at a current of between 25 and 30 amperes. A small stainless steel bridge was placed on the foil over the germanium disc as a guide for the gold wires in the alloying process and contamination of materials is minimized by alloying in an atmosphere of hydrogen.

The furnace was prepared by flushing it thoroughly with hydrogen and then passing a current through the element sufficient to raise it to red heat. This occurs at approximately twice the current required for alloying. As a safety precaution a heavy lucite cover is placed over the furnace.

The bridge from the alloying furnace and the tweezers used for the subsequent operations were cleaned in Aqua Regia, rinsed and dried.

After preparing the materials and furnace as described above, a germanium disc was removed from the distilled water, rinsed in alcohol and placed at the centre of the heating element of the furnace. The stainless steel bridge was positioned over the disc and the pieces of gold wire inserted in the guides Fig. 3. The glass envelope was

Fig. 2

The alloying furnace. We thank Dr. J. Shewchun for the loan of this furnace. It contains a nichrome foil which can be heated in a protecting atmosphere of hydrogen.

Fig. 3

This shows the stainless steel bridge used to guide the gold wires and a germanium disc in position for alloying. During the alloying operation the ends of the wires fuse to the germanium disc.

replaced over the "O"-ring and hydrogen passed at a low rate for several minutes.

The heater current was slowly increased until the alloying point was reached when a small bead of alloy appeared on the surface of the germanium at the foot of each gold wire. The temperature was then held constant as the wire fed through the guides under its own weight until the diameter of the junction was approximately twice that of the wire. After reducing the current slowly to avoid straining the junctions, the hydrogen was turned off and the bolometer element removed.

This procedure usually gives good mechanical strength although occasionally, when an element was being mounted, the alloyed region broke away from the germanium or the wires snapped above the junction. This is thought to be due to the brittle nature of the eutectic.

The completed element was then etched in 30% dilute CP-4 for about four seconds to clean the junctions. The etch was flushed away and the element washed continuously in distilled water for at least twenty-four hours. If any elements were not mounted immediately, they were stored under vacuum until required. This procedure was found necessary as the alloyed regions are very susceptible to the acids. One batch was inadvertently destroyed by leaving it in water after only briefly rinsing the elements.

c. Mounting the Bolometer Elements

A transistor header provides a reliable feedthrough giving both a vacuum seal at low temperatures and good electrical insulation. The T.O.-5 type is suitable for elements of the sizes used (0.25" and 0.125" diameter) and there has been no failure of the glass-to-metal seal of five of these after a total of over one hundred temperature cycles.

The gold wires on the element were bent at the required length, tinned and soldered to the header with pure indium. A lower melting point indium alloy* was used for soldering the header to the condensing cone.

The element is thus supported in a strain free manner, Fig. 4, and by changing the diameter, length and composition of the leads, the thermal conductance from the germanium to the bath may be varied.

The arrangement described gives thermal time constants of 3 mS for a 0.25" disc at $2^{\circ}K$ and 6 mS for a 0.125" disc at $4.2^{\circ}K$.

This technique has also been used for making 2- and 4-terminal elements. Tests have shown that the 4-terminal element does not have a significantly different current noise from the 2-terminal element and it is more difficult to construct and mount.

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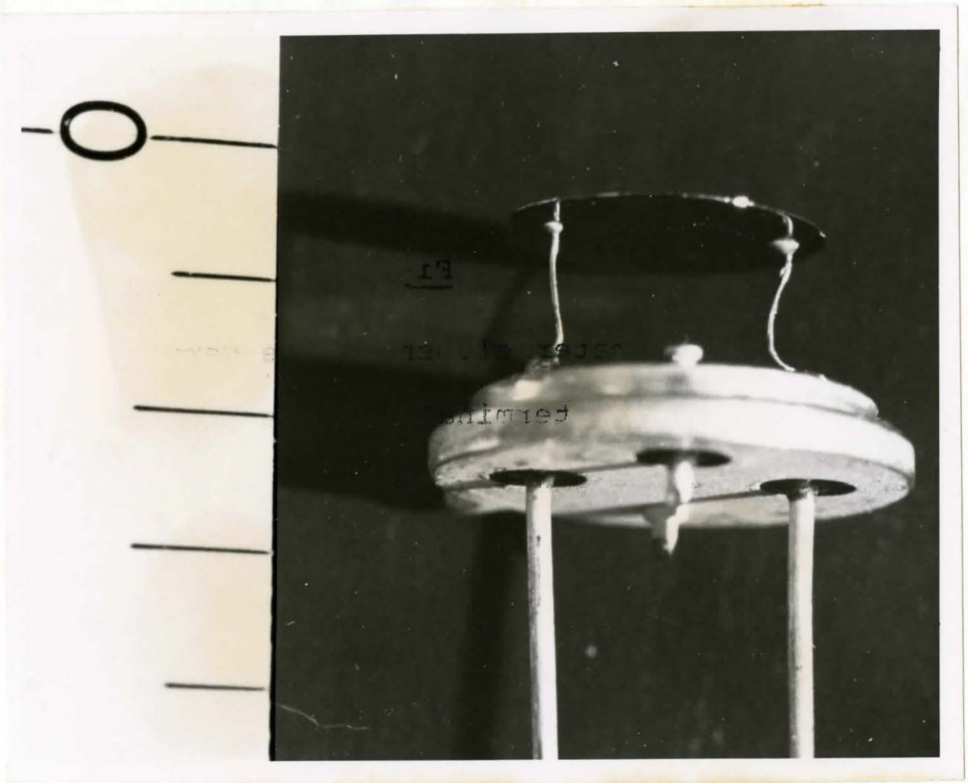
* Indium Corporation of America, Alloy No. 5.
(25% In, 37.5% Sn, 37.5% Pb)

Fig. 4

The mounted bolometer element. The germanium wafer can be seen joined to the terminals of the transistor header by the fine gold wires which provide the thermal and electrical contacts. The scale divisions shown are 0.1 inches.


0

Measurements

Two types of electrical measurements have been made on the bolometers; the determination of the d.c. characteristics and the a.c. measurements of both the signal and the noise. A diagram of the bolometer drive and output circuits is given in Fig. 5.

Mercury batteries*, which have been found to give a very steady e.m.f., are mounted inside the control box and are used to drive the bolometer element with a constant bias current of between 0 and 15μA. For the d.c. measurements an additional mercury cell and a wire-wound precision potentiometer together with a reversing switch are incorporated in the drive circuit. These provide the fine control necessary for the V-I characteristics and also the means of overcoming stray thermal and other e.m.f.'s by reversing the potential. The a.c. measurements were made with some of the mercury cells connected directly across the input terminals to avoid the possible noise from the sliding contact of the potentiometer.

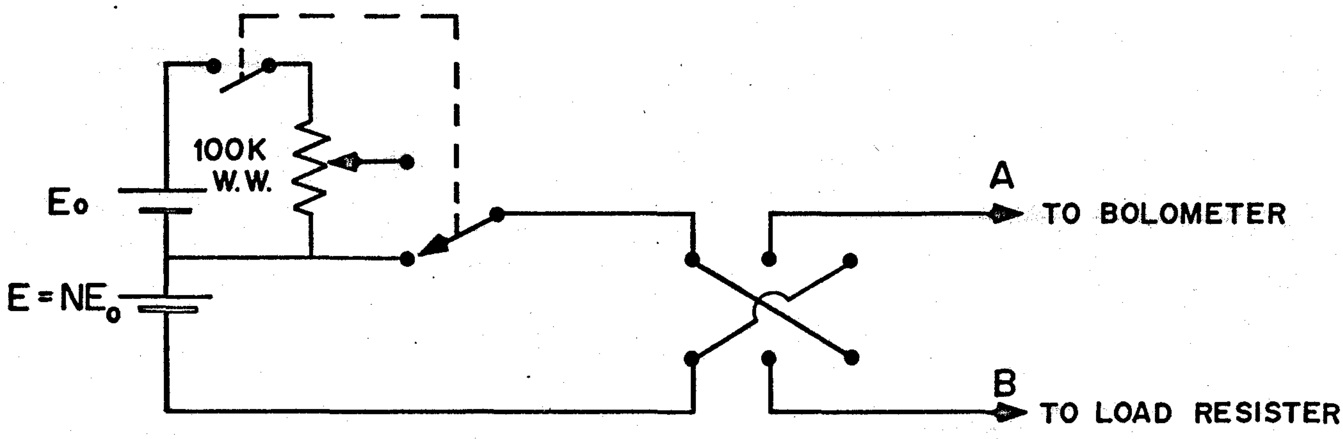
The output circuit may be switched for d.c. measurements to either the wire-wound precision load resistor or the element itself so that the bias current and the bolometer resistance may be determined. The output may

* Eveready 640.

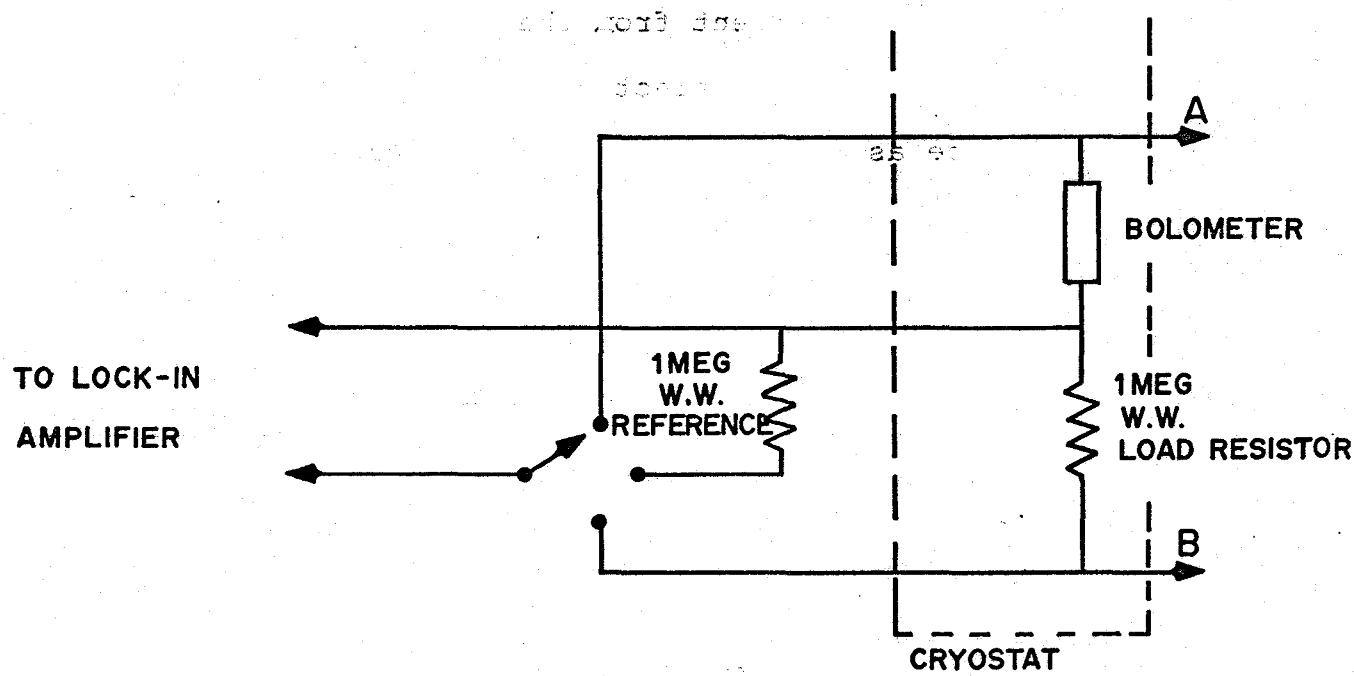
Fig. 5

Drive and output circuits. The drive circuit provides a variable bias current from the mercury batteries. The output circuit can select a megohm resistor for a noise reference as well as the load resistor or bolometer at 4.2°K.

FIG 5.



(a) SCHEMATIC DRIVE CIRCUIT.



(b) SCHEMATIC OF OUTPUT CIRCUIT.

also be switched to a precision wire-wound 1 Megohm resistor inside the bolometer control box so that reference noise measurements may be made under the same conditions as those made on the bolometer itself. The switches used have silver plated contacts on ceramic wafers.

The signal from the bolometer is amplified by a lock-in amplifier* and recorded both by a pen recorder and on a digital voltmeter with paper tape output, Fig. 6a. The optical signal is derived from the chopped radiation from a high pressure mercury vapour lamp in the interferometer and the reference signal for the lock-in amplifier is obtained from the interferometer chopper. The chopper motor was designed to operate from a 50 or 60 Hz supply giving a chopping rate of 12.5 or 15 Hz, but by using a signal generator and a power amplifier chopping rates of between 7.6 and 47 Hz can be obtained.

Noise measurements have been made by averaging the squared output from the lock-in amplifier using an analogue squarer,** Fig. 6b. The noise spectrum of a precision 1-Megohm wire-wound resistor*** obtained using this arrangement is shown in Fig. 7. Measurements have also been made by observing the noise directly on a pen recorder and agreement has been obtained between these methods.

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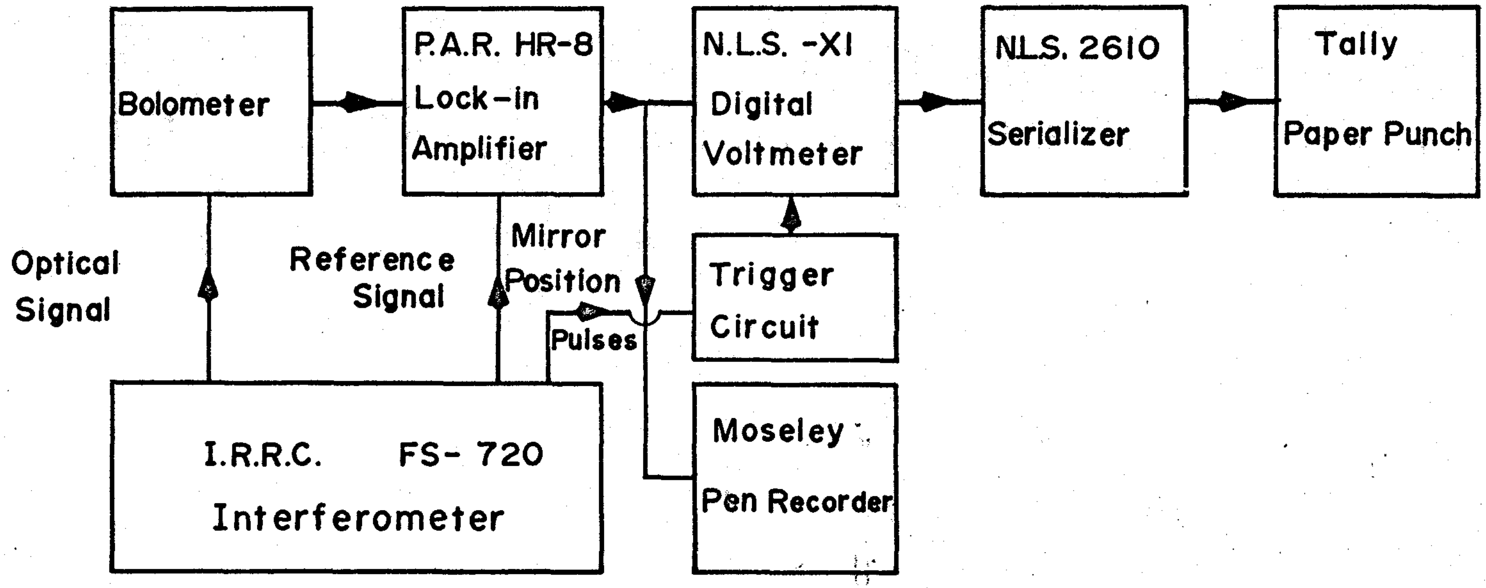
* Princeton Applied Research, Model HR-8 with Type A Preamplifier used single-ended and with remote adapter.

** Philbrick Multiplier Q3M1.

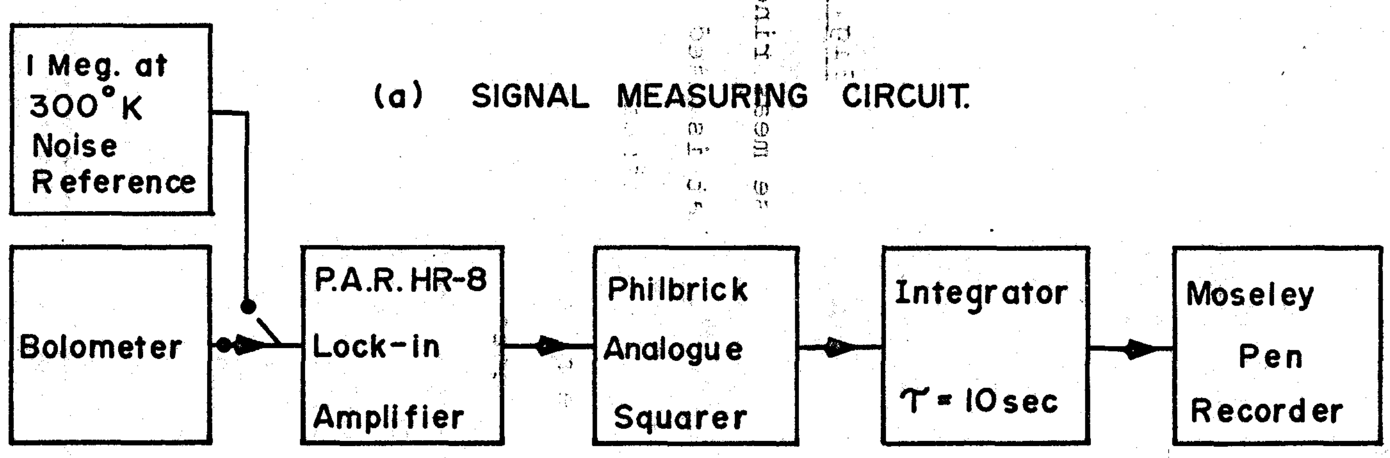
*** Tel Labs type SA-2.

Fig. 6

The signal and noise measuring circuits. The signal circuit is the same one that is used in obtaining interferograms from the spectrophotometer. The noise measuring circuit gives the mean square noise of the element at selected bias currents.



(a) SIGNAL MEASURING CIRCUIT.



(b) NOISE MEASURING CIRCUIT.

FIG 6.

Fig. 7

The noise spectrum of a 300°K wire wound 1 Megohm resistor. The observed noise agrees well with the theoretical Johnson noise. Above 150 Hz the noise is attenuated by the shunt capacitance of the cables. There is a slight amount of excess noise, probably due to the amplifier.

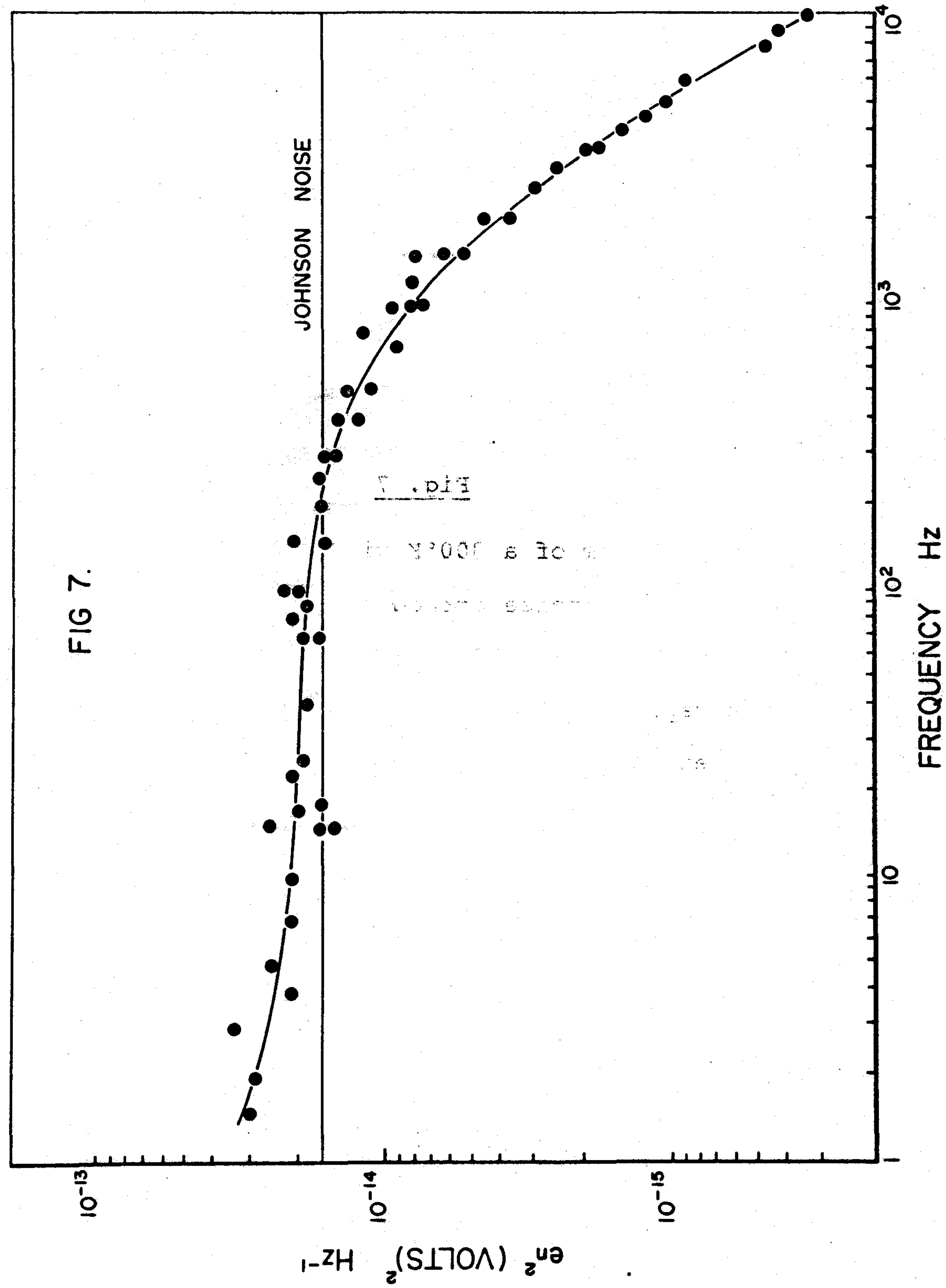


FIG 7.
JOHNSON NOISE
FREQUENCY Hz
1
10
10^2
10^3
10^4
10^-13
10^-14
10^-15
en^2 (VOLTS)^2 Hz^-1

It is necessary to take precautions against mechanical and electrical interference which produce noise especially at the chopping frequency. The whole system is mounted on a rigid concrete basement floor and the interferometer rests on a dolomite slab weighing over 500 pounds which is flexibly mounted in a rigid iron frame.

Fluctuations in the temperature of the helium bath were caused by an oscillation in the pumping line when working at $2^{o}K$. This was eliminated by ballasting the line with a 12-litre reservoir. A low-frequency fluctuation was caused by a return-line bubbler at $4.2^{o}K$ which was overcome by venting the end of the long helium return line to the atmosphere.

The precision 1-Megohm wirewound load resistor is cooled in the liquid helium to reduce thermal noise. Although it is non-inductively wound, it is necessary to prevent the resistor from vibrating in the helium. Several examples of this encapsulated type have been temperature cycled many times with complete reliability.

Constantan wire, 0.012" diameter, is used in the cryostat as it has a lower thermal conductivity than copper. It was sleeved with teflon giving satisfactory insulation as twisted enamelled wires are not reliable and polyethylene tubing fractures easily in liquid helium.

EXPERIMENTAL RESULTS AND DISCUSSION

The characteristics of a typical germanium bolometer used in these experiments are given in Table 1.

Table 1

T_o	temperature of bath	4.2^oK
a	area of bolometer element	$0.08\ cm^2$
t	thickness of bolometer element	0.01 cm
c	thermal capacity of bolometer element	$0.44\ 10^{-6}$ joules $deg^{-1}K$
R_L	load resistance	1 Megohm
R	bolometer resistance	330 K ohm
P	bias power	$5.6.10^{-6}$ watts
S	responsivity at 15 Hz	$1.2.10^4$ volts $watt^{-1}$
τ	response time constant of bolometer	0.006 sec
f	chopper frequency	15 Hz
G	thermal conductance to heat sink	watts $deg^{-1}K$
N.E.P. experimental	noise equivalent power	$1.0.10^{-12}$ watts

The thermal response time constant was measured by observing on an oscilloscope the response to the chopped

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input radiation and also by measuring the frequency response of the bolometer, Fig. 8. The rise time observed on the oscilloscope was 6 mS whereas the frequency response gives a time constant of 16 mS. The first is more characteristic of the element itself whereas the other probably involves the thermal capacity of the supporting wires which contribute at low frequencies, resulting in a lower frequency response.

Using the 6 mS as time constant of the element, a value of G, the thermal conductance to the bath may be determined. The thermal capacity c of the element is given[3] by

$$c = 6.8\ T^3\ v = 0.44.10^{-6}\ \text{joules deg}^{-1}\text{K} \quad (13)$$

where the value v is calculated from the area a and the thickness t of the element. From equation (13) G is found to be 58.10^{-6} watts deg^{-1} and T is 4.3°K.

An example of a static characteristic is shown in Fig. 9. This was measured with the cold shutter in place to avoid raising the temperature of the element except by joule heating. The characteristic is symmetrical about the origin but the value of the thermal conductivity G deduced from it is smaller than that above and further varies very rapidly with T. This indicates that the junctions probably have diode characteristics.

Fig. 8

Observed frequency response of the bolometer. The time constant of the bolometer is 6 ms but there seems to be a 16 ms component probably due to the heat capacity of the supporting wires.

FIG 8.

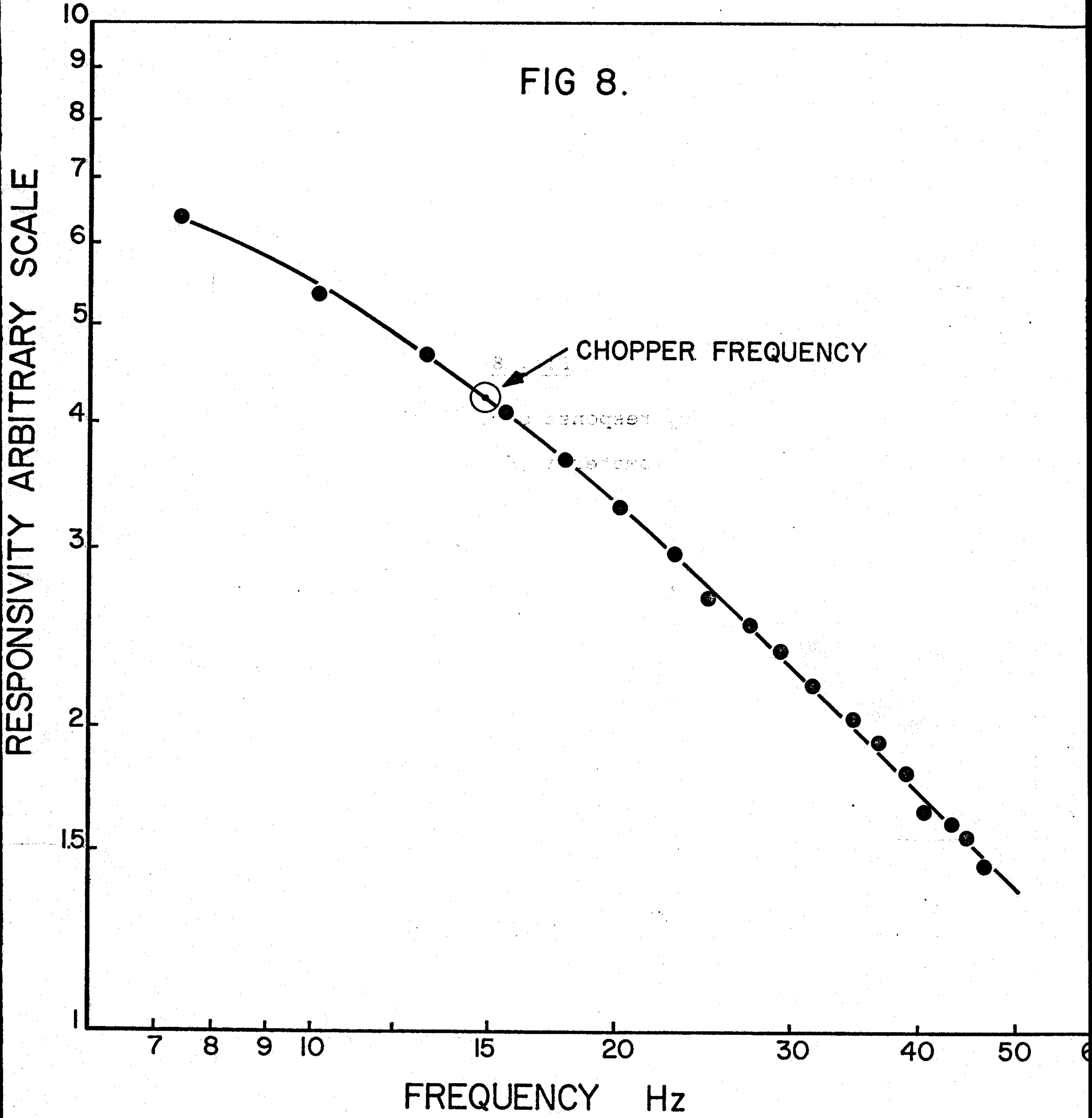
10
9
8
7
6
5
4
3
2
1.5
1
RESPONSIVITY ARBITRARY SCALE
CHOPPER FREQUENCY
7
8
9
10
15
20
30
40
50
FREQUENCY Hz

Fig. 9

The current voltage characteristic of the bolometer. Part of the curvature seen here we attribute to the presence of rectifying junctions in the material.

FIG 9.

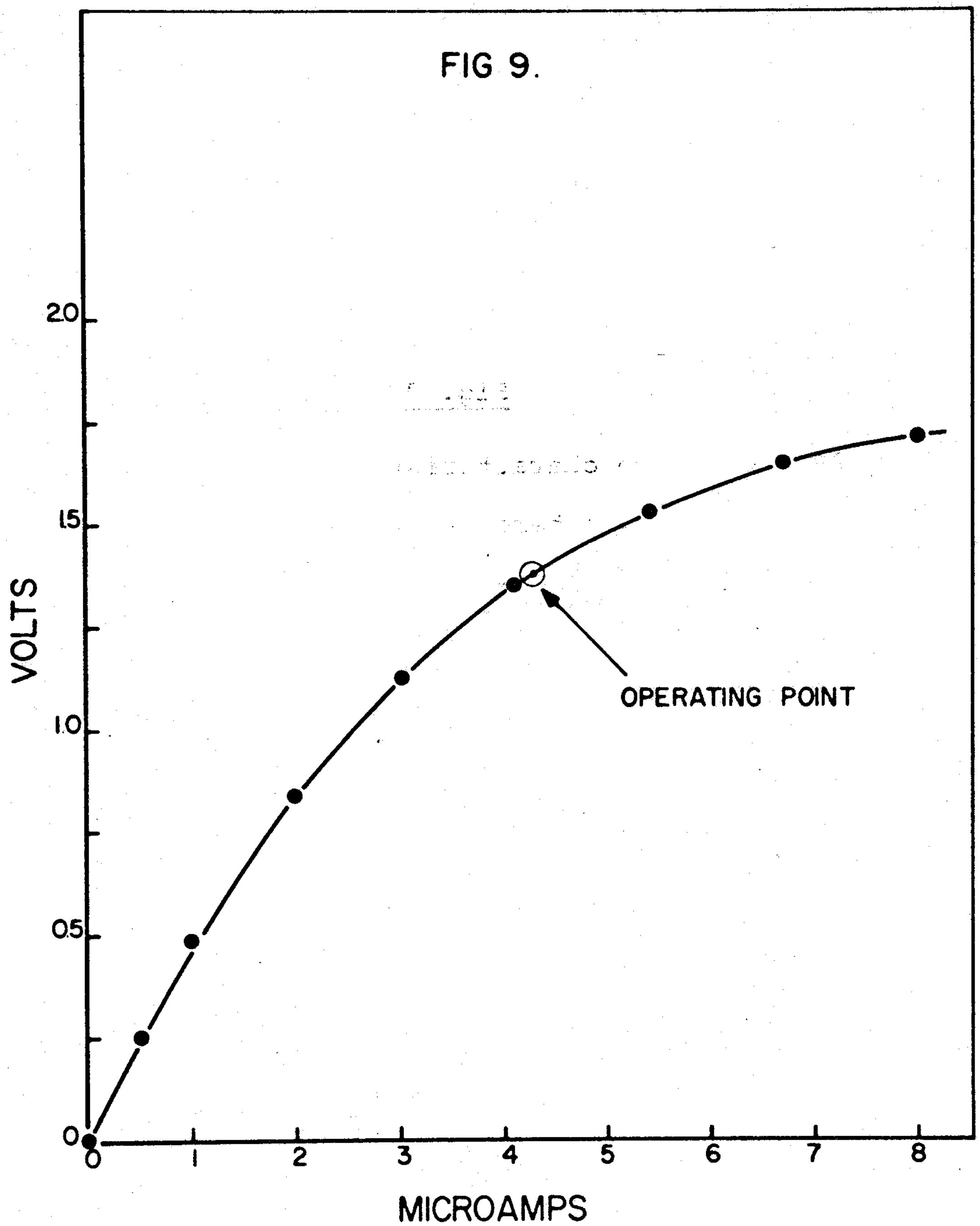

Fig. 10

Bolometer output as a function of bias current. The operating point has been chosen to optimize the signal to noise ratio.

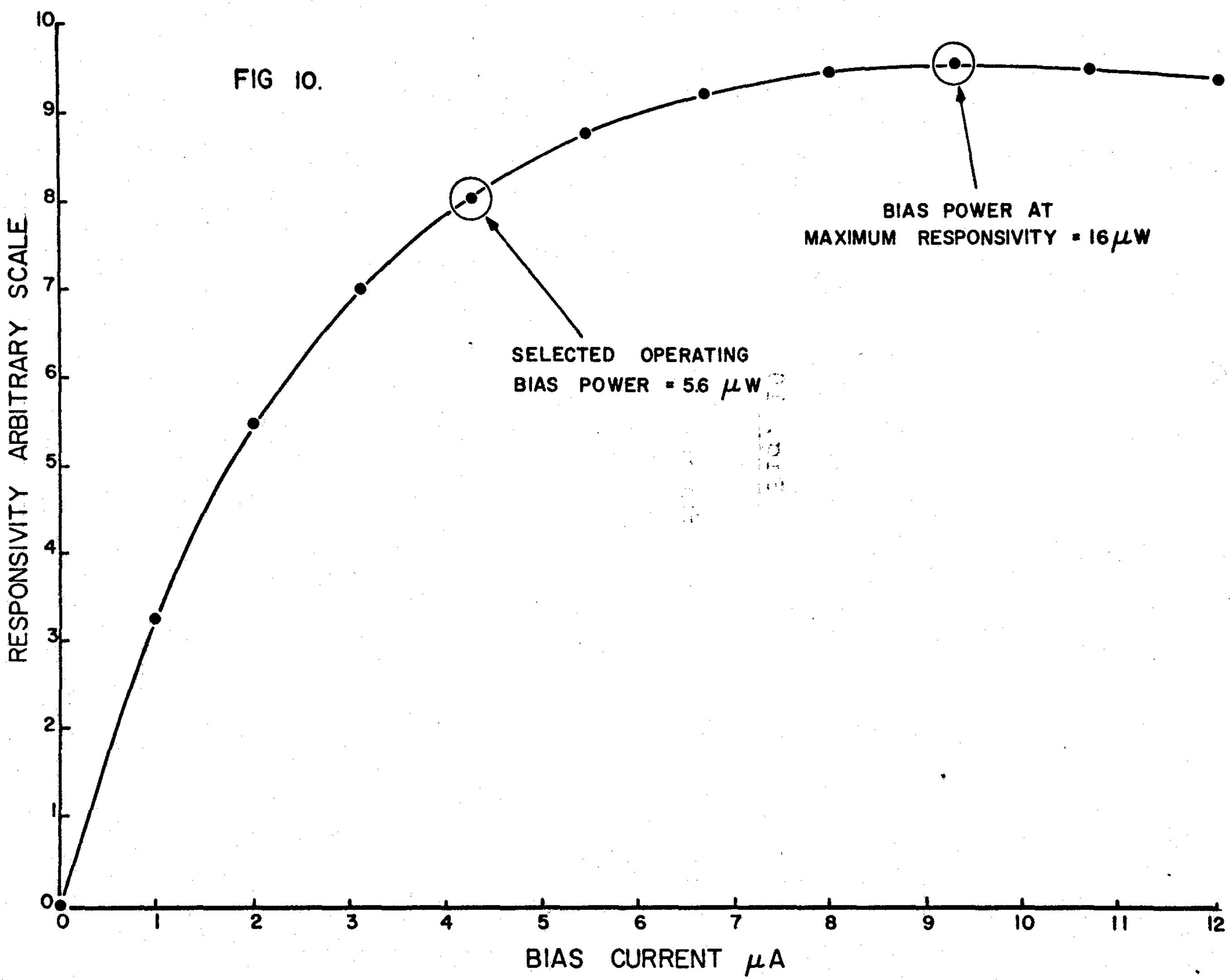
FIG 10.
RESPONSIVITY ARBITRARY SCALE
BIAS CURRENT μA
SELECTED OPERATING
BIAS POWER = 5.6 μW
BIAS POWER AT
MAXIMUM RESPONSIVITY = 16 μW
0
1
2
3
4
5
6
7
8
9
10
11
12

The operating point on the static characteristic was selected by measurement of the signal to noise ratio. The low frequency responsivity given by equation (5) is $2.0.10^4$ volts watt^{-1} at this bias power ($5.6.10^{-6}$ watts) and compares with the theoretical maximum S_{max} (given by equation (11)) of $2.6.10^4$ volts watt^{-1} at a bias power of 25.10^{-6} watts. The responsivity was shown experimentally to be a slowly varying function of current in this region, Fig.10.

The angular acceptance of the bolometer which determines the aperture through which the background noise and also the signal are viewed was determined experimentally and the results shown in Fig. 11. This was obtained by moving a black body source in the horizontal plane at a constant distance from the bolometer entrance pupil and a mechanical chopper placed in front of the bolometer provided the reference signal for the lock-in amplifier. The graph shows that the bolometer has a rather narrow field of view due possibly to a slight misalignment of the filter compartment. This decreases the background radiation and its associated noise power but does not seriously affect the optical efficiency of the bolometer in its present application.

The combination of filters used (KBr crystal plus quartz and black polyethylene) has the property of absorbing

Fig. 11

The measured angular aperature of the bolometer. The curve shows the bolometer to have a narrow aperature.

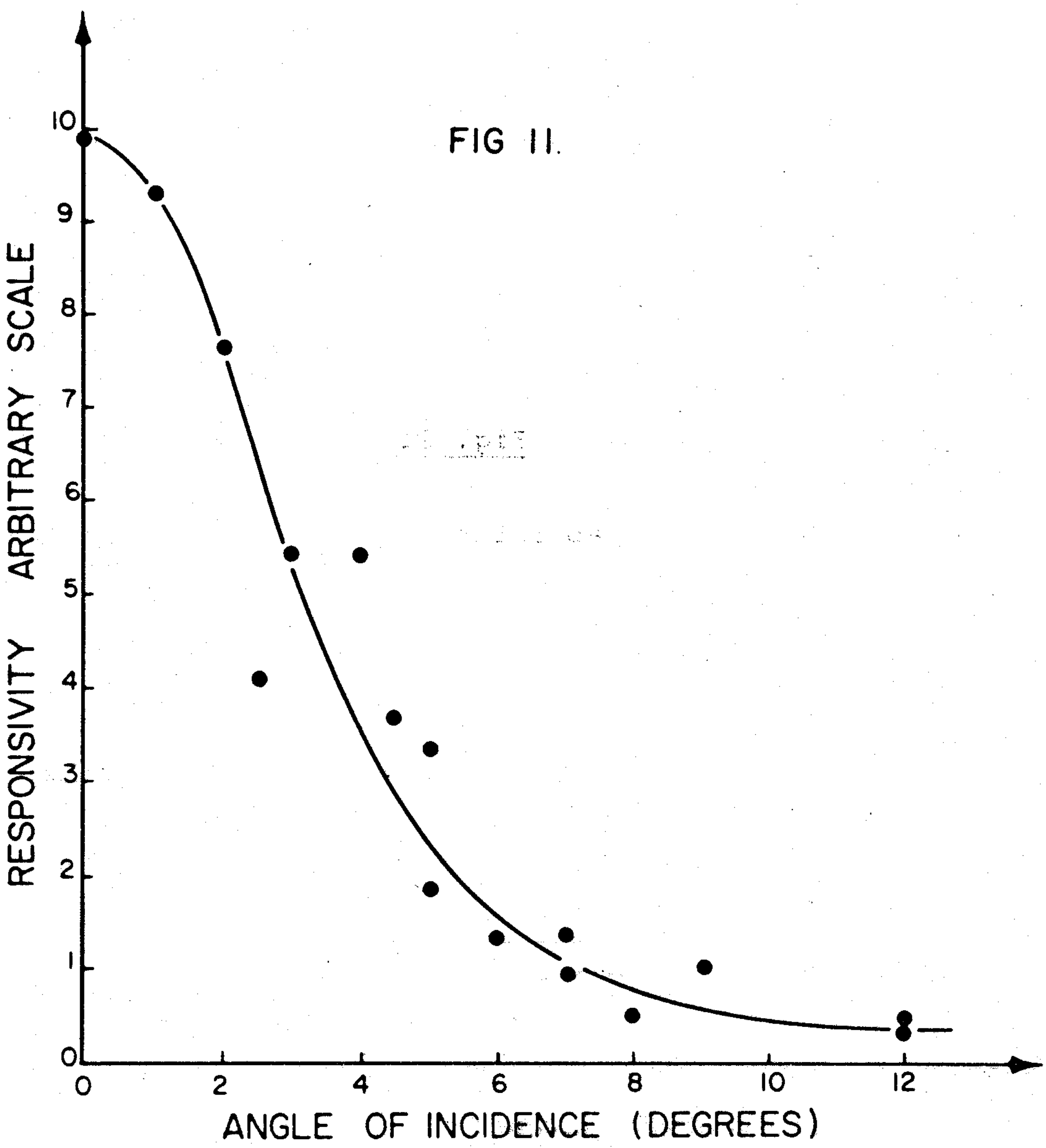
RESPONSIVITY ARBITRARY SCALE
ANGLE OF INCIDENCE (DEGREES)
0
1
2
3
4
5
6
7
8
9
10
0
2
4
6
8
10
12

FIG 11.

all radiation to 100 cm^{-1} and transmitting beyond that point. This has the effect of reducing both the radiation incident on the bolometer and also the noise power associated with it. From the spectral distribution of the background radiation noise, it has been calculated that the square of the noise power is reduced to 0.15% of its unfiltered value.

Under these operating conditions the independent contributions to the total noise power of the bolometer given in equation (7) may be evaluated for the case when the bolometer is operated at 15 Hz and has no excess noise: Table 2.

Table 2

Contributions to the Noise Power

Source	Noise Power watts	
Johnson	$4kT\ R\ S^{-2}$	100.10^{-14}
Temperature	$4kT^2\ G$	24.10^{-14}
Radiation from bolometer	$8\varepsilon\sigma kAT^5$	$0.019.10^{-14}$
Background radiation	$8\varepsilon\sigma kT_b{}^5 Sin^2\ \theta/2$	$1.5.10^{-14}$

Excess noise has been detected and is the difference between the experimental noise power and the noise power predicted from the above.

The absolute responsivity of the bolometer was measured using a calibrated source consisting of a black body at $425^{o}K$. The output was measured using the signal measuring circuit of Fig. 6a. The experiment was carried out in an atmosphere of dry nitrogen gas to minimize absorption due to water vapour and corrections were made for the radiation emitted from the chopper blades, the effect of the filters in both absorbing and reflecting radiation and the reflectivity of the germanium. Other factors taken into account were the mismatching of the condensing cone to the element and the effective responsivity at 15 Hz due to the finite size of the load resistor and the response time of the element.

This experiment was repeated for a different radiation output and correlation to within 30% was obtained between the theoretical and experimental results and it is concluded that the bolometer does inherently possess the responsivity predicted theoretically.

In the absence of excess noise the theoretical N.E.P. of 1.10^{-12} watts may be obtained by adding vectorially the independent terms of Table 1. The inherent N.E.P. of 80.10^{-12} for the detector is obtained by taking its actual measured noise from the appropriate noise spectrum at the operating frequency and dividing it by the calculated responsivity.

The noise spectra are shown in Figs. 12, 13 and 14.

Fig. 12

Measured noise power with zero bias current. We attribute the noise below 10 Hz to the amplifier. Between 10 Hz and 100 Hz there is excess noise due to microphonic oscillations induced by the liquid helium.

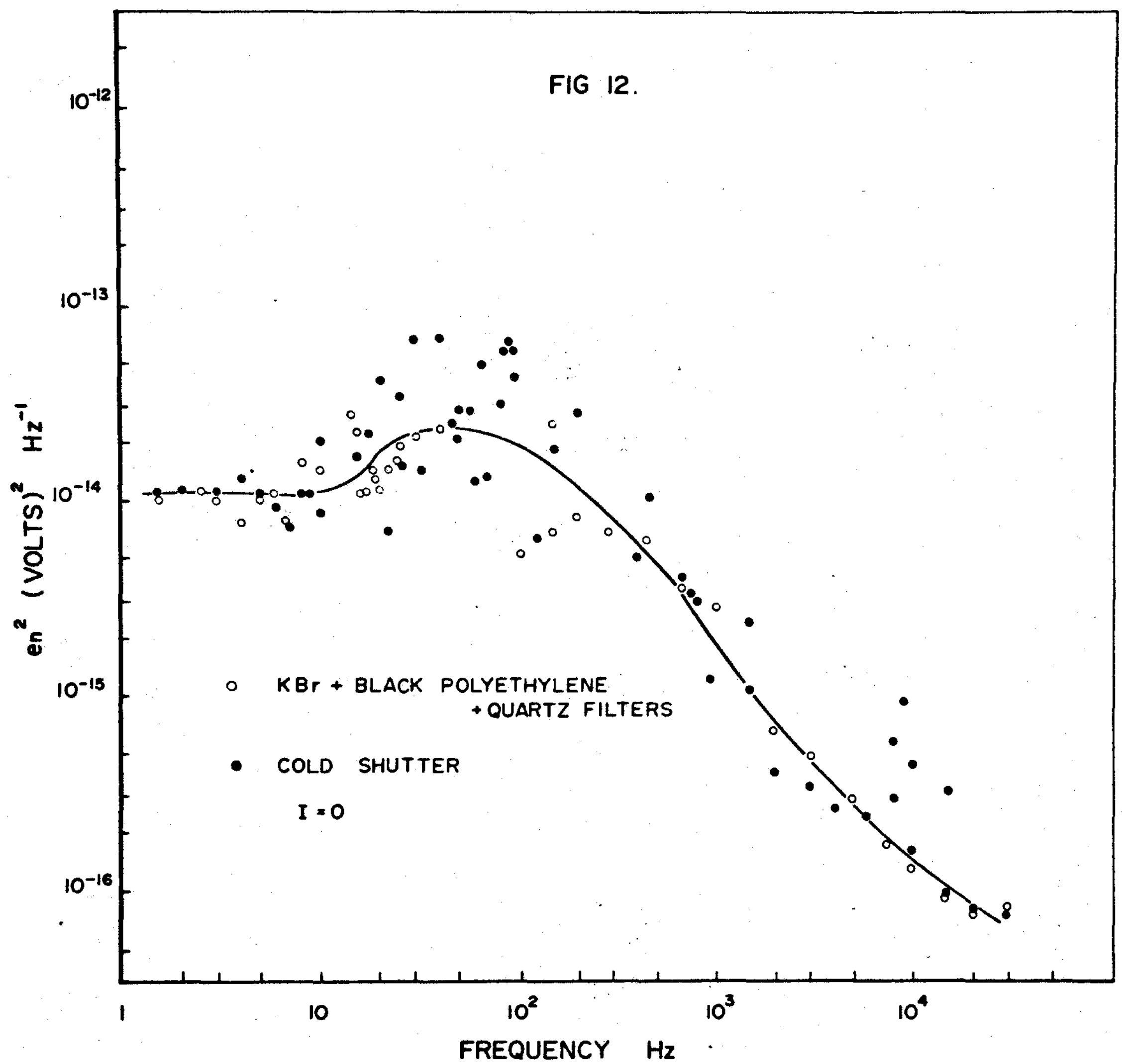

FIG 12.
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
en^2 (VOLTS)^2 Hz^{-1}
KBr + BLACK POLYETHYLENE + QUARTZ FILTERS
COLD SHUTTER
I = O
1
10
10^2
10^3
10^4
FREQUENCY Hz

The attenuation at frequencies above 400 Hz is due to the time constant of the amplifier input circuit. Fig. 12 shows a constant noise level at low frequencies and an intermediate frequency range within which resonances occur. These resonances are thought to be due firstly to microphonic effects induced by the liquid helium in the cryostat and also to temperature fluctuations associated with acoustical resonances in the dewar and pipes above the liquid helium. Recent experiments have shown that this excess noise is reduced by modifications to the venting system.

The current dependent nature of the excess noise is illustrated by Figs. 13 and 14. The inherent noise in this system at any frequency may be taken from the graphs to obtain the inherent N.E.P. from the theoretical responsivity. The radiation has no effect on the measured noise as would be expected from the calculation.

The optical and electrical efficiency of the system does not permit this N.E.P. to be realized and the absolute responsivity measurement gives the overall experimental N.E.P. of 2900.10^{-12} watts. This is due to optical losses in the filter compartment, light pipe, etc. These values are given in Table 3.

Fig. 13

Noise power with 2 μa bias current. Below 10 Hz 1/f noise can be seen.

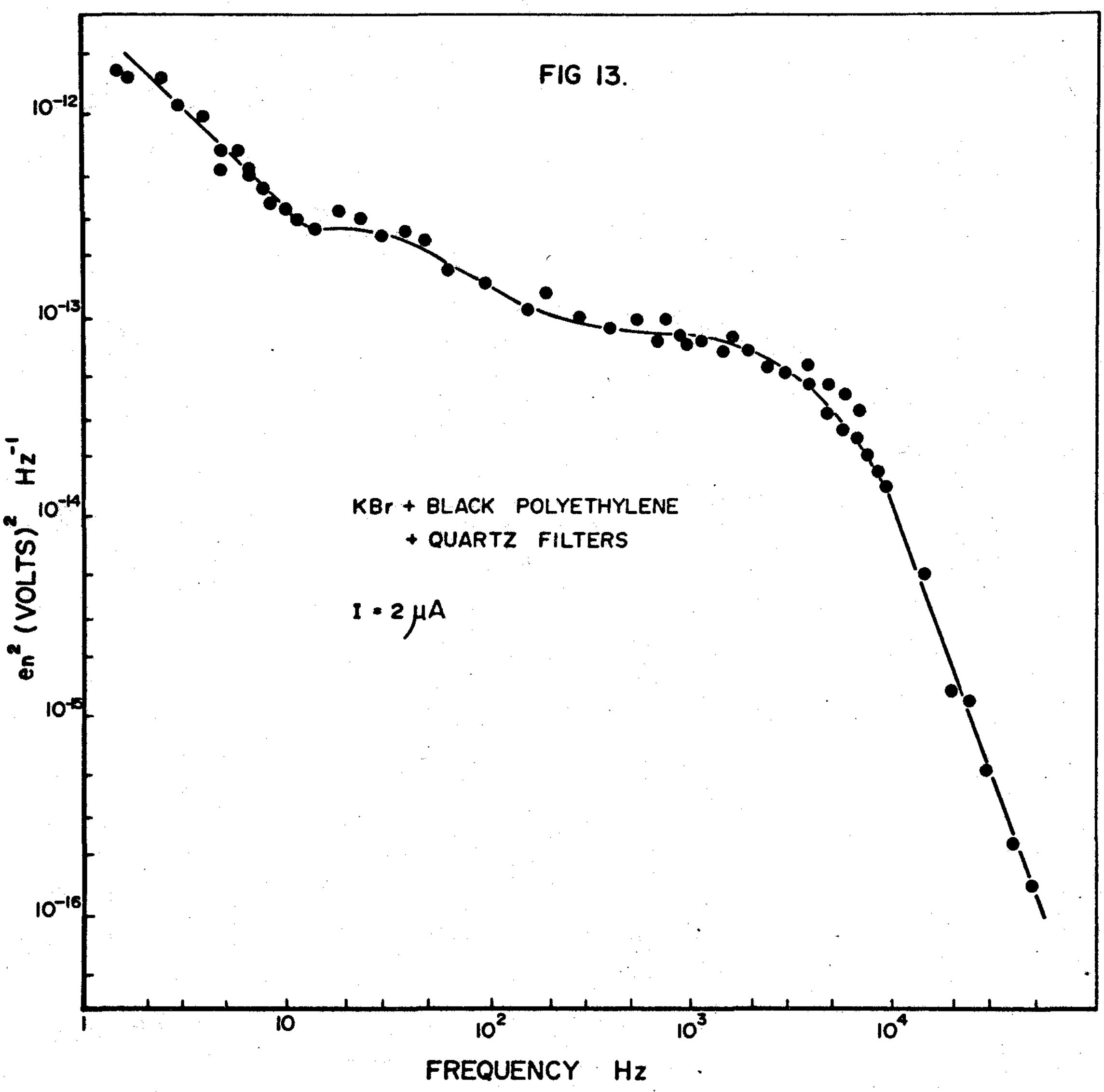
FIG 13.
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
en^2 (VOLTS)^2 Hz^{-1}
KBr + BLACK POLYETHYLENE
+ QUARTZ FILTERS
I = 2 μA
1
10
10^2
10^3
10^4
FREQUENCY Hz

Fig. 14

Noise power spectrum with 4.25 μA bias current. This current gives the optimum signal to noise ratio. Note the very strong 1/f noise. The filtered external radiation has little effect on the measured noise.

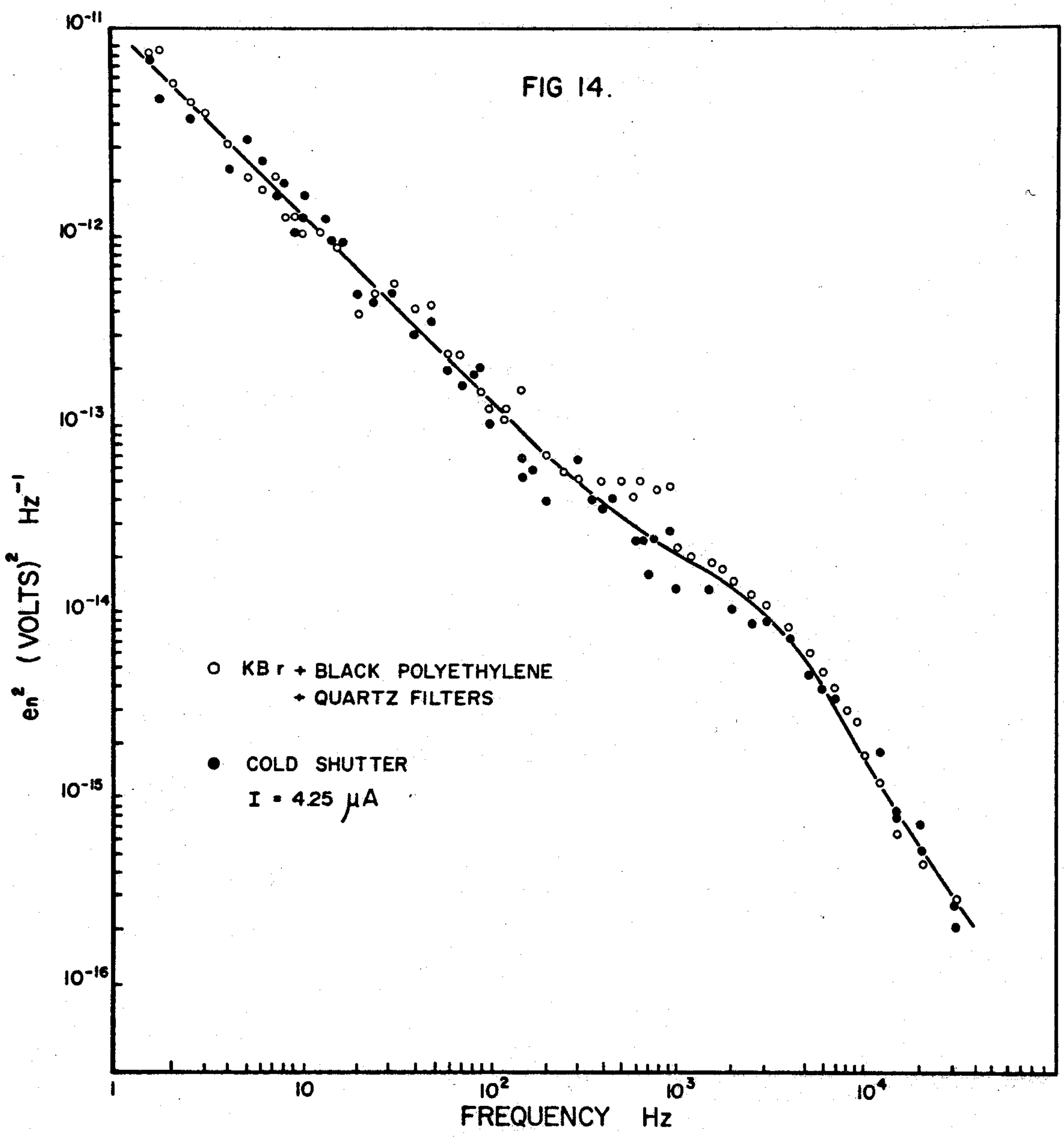
FIG 14.
O KBr + BLACK POLYETHYLENE
+ QUARTZ FILTERS
● COLD SHUTTER
I = 4.25 μA
e_n^2 (VOLTS)^2 Hz^{-1}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
1
10
10^2
10^3
10^4
FREQUENCY Hz

Table 3

Noise Equivalent Power (watts)

Theoretical	Inherent	Experimental
1.10^{-12}	80.10^{-12}	$2,900.10^{-12}$
with improved venting and optical alignment	36.10^{-12}	100.10^{-12}

Note: The excess noise due to temperature fluctuations has been reduced, since these calculations were made, giving a latest measurement of the inherent N.E.P. of 36.10^{-12} watts for the same detector. Further, realignment of the optical system together with a more effective method of flushing water vapour from the light pipe by venting the top to the atmosphere has resulted in an improvement in the optical efficiency of the system currently giving an experimental overall N.E.P. of 100.10^{-12} watts.

Some samples taken from spectra obtained using the bolometer as the detector for the interferometer are given in Figs. 15 and 16. They show that by using the bolometer the theoretical resolution inherent in the interferometer is obtained in the far infrared.

A simpler optical system containing a single filter is being prepared for use with the Perkin-Elmer 301. This

Fig. 15

A typical absorption spectrum obtained with a Fourier interferometer using the germanium detector. Note the low noise in this high resolution spectrum. The peak shown is due to a localized mode of Cl^- in KBr.

FIG 15.

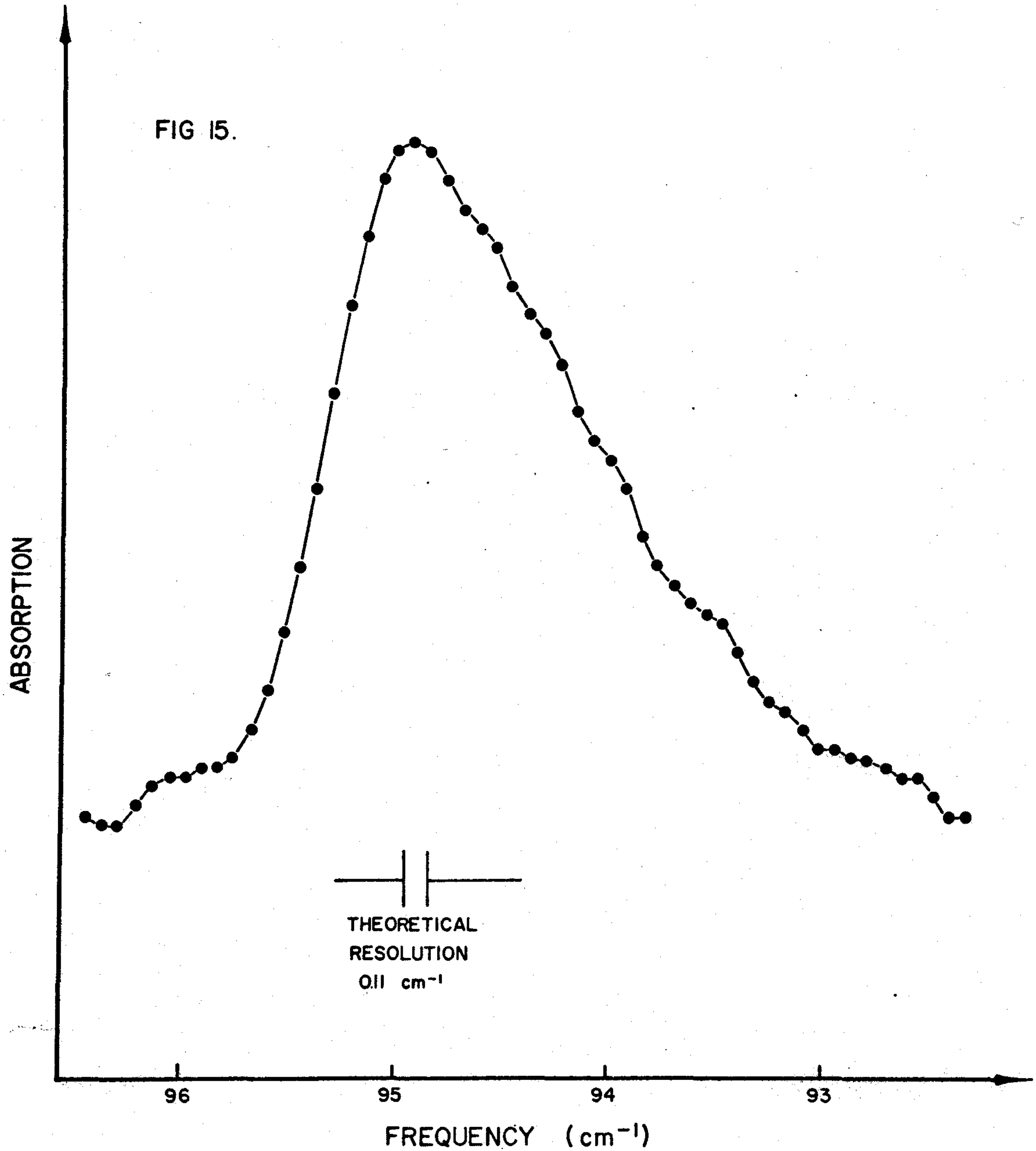
ABSORPTION
THEORETICAL
RESOLUTION
0.11 cm⁻¹
96
95
94
93
FREQUENCY (cm⁻¹)

Fig. 16

Some typical water vapor lines in the far infrared. The doublet on the right is separated by 0.26 cm^{-1}. From the widths of the lines it can be seen that the system operates at theoretical resolution .

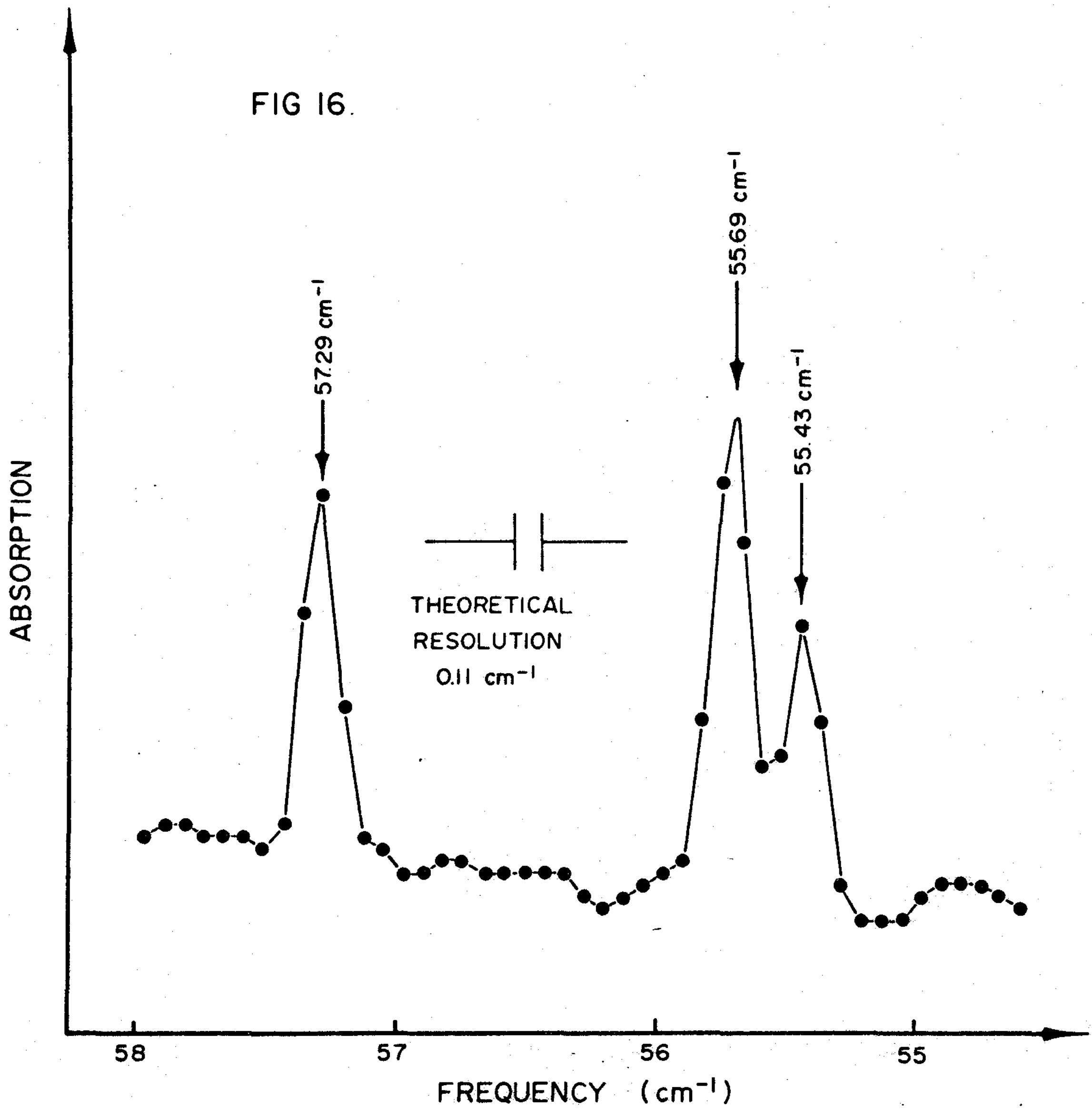
FIG 16.
ABSORPTION
57.29 cm⁻¹
55.69 cm⁻¹
55.43 cm⁻¹
THEORETICAL
RESOLUTION
0.11 cm⁻¹
58
57
56
55
FREQUENCY (cm⁻¹)

system will fit into a conventional helium storage dewar and it is anticipated that this arrangement will be more optically efficient and less susceptible to noise than the more versatile system used with the interferometer. This means however, that it will be necessary to continue using the conventional optical dewars for cooling the samples under investigation, thereby reducing the overall optical efficiency. The storage dewar system will be, however, an excellent radiometer.

Some preliminary investigation has been carried out on the operation of bolometers at the temperature of pumped helium using elements of a lower resistivity material. One example was used successfully as a detector and some improvements over the performance of the $4.2^{o}K$ bolometer were obtained. It is felt, however, that a further investigation of both the electrical properties of the gold-germanium junctions and the sources of noise in the cryostat should be made before the advantages of working at lower temperatures can be fully realized.

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