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SEMIANNUAL PROGRESS REPORT NO. 3

ON

FREQUENCY MULTIPLICATION IN HIGH-ENERGY ELECTRON BEAMS

This report covers the period October 1, 1967 to March 31, 1968

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1. General Introduction (G. I. Haddad)

This report covers the work performed during the period October 1, 1967 to March 31, 1968. The various tasks which are presently active under this program include:

a. Relativistic electron-beam devices for millimeter-wave generation.
b. Beam-plasma interactions for amplification and harmonic generation.
c. Electron-beam cyclotron instabilities for harmonic generation.
d. Millimeter- and submillimeter-wave detectors.

The first three tasks have been described previously and the work performed during this period is summarized in the following sections of this report. The fourth task, namely, millimeter- and submillimeter-wave detectors was initiated recently under this program. The basic detection schemes are described and the work performed to date is summarized in the following sections.

2. Relativistic Electron-Beam Device

Supervisor: J. E. Rowe
Staff: G. T. Konrad

The object of this phase of the program is the generation of millimeter-wavelength radiation by use of a tightly bunched, relativistic electron beam. The experimental setup has been described briefly in a previous progress report.

As mentioned in the last progress report, difficulty was encountered with beam transmission through the high-voltage anode. The very erratic behavior of the collector current was believed to be due to charging of the quartz cone through which the beam passes. Therefore, a new quartz cone was installed with the beam tunnel increased to a diameter of 3 mm from 2 mm. A thin layer of copper, approximately one third of a skin-depth thick at a wavelength of 2 mm (corresponding to a thickness of slightly over 500 Å), was deposited along the inside of the beam tunnel. This should help in draining off the negative charge deposited by that fraction of the beam intercepted by the quartz.

All these modifications have been made and testing of the device is scheduled to be resumed in the very near future.

3. Beam-Plasma Interactions

Supervisor: R. J. Lomax

Staff: J. D. Gillanders

3.1 Experimental Phase. The object of the experimental part of this study is to investigate the possibilities of building a beam-plasma system which operates at a uniform pressure. Previous systems have required complex vacuum systems in order to maintain a very low pressure in the area of the electron gun which produces the beam, and at the same time to maintain a higher pressure in the plasma-generating region. The cold-cathode plasma electron gun appeared to provide a solution for this problem since it operates in the pressure range which is convenient for plasma generation. Thus the whole system can operate at the same pressure.

A 10,000-volt power supply was used to test the plasma electron gun. A small beam was obtained within a large negative-glow plasma. The reaching distance of the beam was small and the entire system fluctuated in time. Thus it does not appear that a stable beam plasma device can be constructed with the present gun in the range of parameters of this experiment: voltage from 0-10,000 volts and pressure from 0-200μ (no beam was obtained at pressures above 200μ).

3.2 Theoretical Phase. The object of the theoretical part of this study is to determine the effect of collisions on the instabilities of a beam-plasma system. This was motivated partly by the knowledge that the cold-cathode electron gun would operate in a pressure range where collision effects in the plasma could not be ignored completely.

In general, collisions tend to provide damping for unstable systems. This can reduce the maximum growth rate of a convective instability or damp out an absolute instability. It is conceivable that in a system containing both convective and absolute instabilities the absolute instability might be damped out before the convective instability. This would allow stable gain to be obtained from a system which would otherwise have produced only oscillation.

The method used in this study is to solve for the roots $k(\omega)$ of the dispersion equation $D(\omega,k) = 0$ of the beam-plasma system using a high-speed digital computer. The work was started on an IBM 7090, but the program had to be rewritten for the IBM 360/67 system which is replacing it. This opportunity was taken to redesign the program using a more efficient method of integration. This method takes an initial guess at the value of k for a given ω and refines it by several applications of Newton's method. Once this initial point has been refined to the desired accuracy, a second point of the root k is predicted for an adjacent value of ω using the derivatives at the initial point. This second point is then refined and both points are used to predict the third, etc. After four points have been found, each new point is predicted by a four-point formula using both the value of the points and the derivatives at those points. In general, only one application of the Newton corrector is necessary. Since this is the only point at which the dispersion function and its derivatives must be evaluated, this method is much more efficient than the Runge-Kutta method used previously which required four evaluations. The roots can be traced with either the real part of ω or the imaginary part of ω as a variable. Thus the ω-k plot can be produced and then Briggs's criterion[1] can be applied to determine the types of instabilities present.

The new program has been checked out and production runs are being started. The dispersion relation will first be studied for the collision-free case. Then the effects of a finite collision frequency will be introduced and the changes observed.

4. Time-Dependent Nonlinear Analysis of Electron-Beam Plasma Interaction

Supervisor: J. E. Rowe

Staff: A. T. Lin

In a beam-plasma system, the same fields are supported by both the plasma and the beam, and the restoring forces to a perturbation depend on the respective beam and plasma densities. If the electron beam density is very small in comparison to the plasma density, the nonlinearity of the plasma is not particularly important in the energy exchange process.

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[1] Briggs, R. J., Electron-Stream Interaction with Plasmas, The M.I.T. Press, Cambridge, Mass.; 1964.

As mentioned by Fainberg[1], this problem can be solved analytically for one-dimensional longitudinal oscillations by introducing a stream function $\psi(t,Z)$ as an independent variable, where $\psi(t,Z)$ is defined by the equations

$$\frac{\partial\psi}{\partial Z} = \frac{n}{n_o} \ , \quad \frac{\partial\psi}{\partial t} = -\frac{nv}{n_o} \ , \tag{4.1}$$

and $\psi(t,Z)$ is invariant along the particle trajectory

$$\frac{d\psi}{dt} = \frac{\partial\psi}{\partial t} + v\frac{\partial\psi}{\partial Z} = 0 \ . \tag{4.2}$$

After the transformation of coordinates from (Z,t) to (ψ,t), the nonlinear partial hydrodynamic equation becomes an ordinary differential equation. The general solution obtained may be fitted to any prescribed boundary or initial value. Shapiro and Shevchenko[2] used this method to study the nonlinear theory of instabilities in a monoenergetic beam of electrons in a system with electrodes.

For a sufficiently dense beam and for operation near the plasma resonance the nonlinear effects on the beam can be neglected. Krasovitskii and Kurilko[3] use the dielectric constant

$$\epsilon = \epsilon_o \left[1 - \left(\frac{\omega_p^2}{\omega^2}\right) \exp\left(-\frac{E^2}{E_o^2}\right)\right] \ , \tag{4.3}$$

---

[1] Fainberg, Ya. B., "Interaction of Beams of Charged Particles with Plasma," Int. Symp. on Beam-Plasma Interaction. Prague, Czechoslovakia; September 4-6, 1967.

[2] Shapiro, V. D. and Shevchenko, V. I., "Contribution to the Nonlinear Theory of Instability of an Electron Beam in a System with Electrodes," Soviet Physics-JETP, vol. 25, No. 1, pp. 92-97; July, 1967.

[3] Krasovitskii, V. B. and Kurilko, V. I., "Theory of Amplification of Longitudinal Waves by a Charged Particle Beam in a Nonlinear Plasma," Soviet Physics-JETP, vol. 24, No. 2, pp. 300-302; February, 1967.

to describe their nonlinear plasma and neglect nonlinear effects in the equations of motion of the beam particles. They calculated the maximal amplitude of the amplified wave and obtained the spatial variation of the field and found that the period of the spatial variation of the amplitude is approximately equal to the reciprocal of the linear theory amplification rate.

When the nonlinear effects on both the beam and the plasma are important, no general theory has yet been obtained. In order to analyze this general case, the system will be represented by discrete disks and the computer will be used to solve the problem. It is anticipated that some results will be obtained in the near future. At the same time we are developing a model which uses the dielectric constant, i.e., Eq. 4.3, to describe the nonlinear effect in the plasma, and discrete sheets to represent the electron beam.

5. The Study of Cyclotron Harmonic Instabilities

Supervisor: W. D. Getty

Staff: A. Singh

This part of the project deals with the investigation of instabilities in a magnetized plasma with an anisotropic velocity distribution:

$$f(v) = \frac{1}{2\pi v_{\perp_o}} \delta(v_\perp - v_{\perp_o})\delta(v_\parallel - v_{\parallel_o}) ,$$

where $v_\parallel$ and $v_\perp$ refer to velocities parallel and perpendicular, respectively, to the magnetic field. The objective of the investigation is to examine, theoretically and experimentally, the feasibility of using these instabilities for electron-cyclotron harmonic generation. A brief review of the subject and an approximate method for determining the instability conditions were given in the previous report.

At the present stage an analysis of the boundary-value problem, "wave propagation through a plasma contained in a metallic cylinder," is being attempted.

The results of such an analysis will be helpful in designing and interpreting the experiments more precisely than is possible at present.

A new experimental tube is under construction. The tube consists of a planar, three-electrode electron gun immersed in a magnetic field. The gun has previously been tested and was found to give satisfactory performance (30 ma at 600 volts). The beam emerging from the gun is passed through a corkscrew and a magnetic-field jump which give the beam the desired velocity distribution. The beam is then made to travel through an input microwave coupler, a drift region and an output microwave coupler. In the drift region a system of probes is introduced to measure the propagation characteristics of the plasma medium. These measurements will be carried out under both stable and unstable conditions of the medium.

6. Nonlinear Lagrangian Analysis of Beam-Plasma Systems* (J. E. Rowe)

Several methods of analyzing the nonlinear beam-plasma and two-stream interaction systems are being investigated using digital computer simulation techniques. In particular, the following problems are being studied:

1. A nonlinear time-dependent analysis of a beam-plasma system. This work is briefly reported on in Section 4. The particular models being investigated include both linear and nonlinear representations of the plasma. The beam is always considered as being nonlinear and the

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* This work is partially supported by the National Science Foundation under Grant GK-1708.

space-charge forces are computed on the basis of interacting disks in the one-dimensional system and on the basis of interacting annular rings of charge in the two-dimensional case. The beam representation has been checked out on the computer for both cases. This work will be reported under Section 4 in the future.

2. A nonlinear steady-state analysis of two-stream interactions (electron-electron, electron-ion and ion-ion) for both one-dimensional and two-dimensional systems. Both streams (in relative motion) are described on a particle basis and may, in fact, have a non-zero temperature. This work will, in the future, be supported under NSF Grant GK-1708 and will no longer be reported here. The basic techniques developed will be applied to Items 1 above and 3 below.

3. A nonlinear steady-state beam-plasma system in which the plasma is assumed to remain linear and is described in terms of a frequency-dependent permittivity. The electron beam becomes nonlinear under modulation and is analyzed as indicated in Items 1 and 2 above. This work will be continued and will be reported under Section 7 since it will specifically be applied to the experimental system described there. The beam representation has been checked out on the computer and the plasma equations are currently being programmed.

In Items 1, 2 and 3 above the electron beam is represented by annular rings of charge in a two-dimensional system and finite, axial, magnetic-focusing fields are considered. In fact the magnetic field may be spatially inhomogeneous. In Item 2 above the second stream is also described in terms of annular rings of charge. The equations have been programmed and checked out on an IBM 7090 computer system including the space-charge integrals. Several check runs are currently being made and a plotting routine to facilitate data presentation and analysis is being checked out. We anticipate making two-stream runs in the near future. Unfortunately the IBM 7090 computer will be replaced by an IBM 360/67 during the latter part of June, 1968, and the equations will have to be reprogrammed. The work during the next period will concentrate on Items 1 and 3.

7. Harmonic Current Generation in a Beam-Plasma System

Supervisor: J. E. Rowe

Staff: G. T. Konrad

This portion of the program concerns itself with the study of harmonic generation and coupling schemes in beam-plasma systems. The theoretical aspect of the work consists of the derivation and solution of nonlinear large-signal equations describing beam-plasma interactions, including higher harmonic r-f components. The plasma column is regarded as a transmission line with lumped circuit components, which can be determined in terms of the various plasma parameters. Other than that, the large-signal analyses of traveling-wave amplifiers are directly applicable to this problem with only minor modifications. One-dimensional as well as two-dimensional models have been considered and the appropriate equations have been derived. Solutions on a digital computer have not yet been obtained however, because a large fraction of the time was spent on the experimental phase of this portion of the program.

A brief description and a sketch of the beam-plasma device were shown in the last progress report. Acquisition and installation of a more porous dispenser cathode and elimination of a boron nitride spacer in the gun region eliminated all the cathode poisoning problems experienced before. A vacuum in the 10^{-7} Torr region can be obtained in the device; the gun has worked well when a xenon plasma was maintained at pressures as high as 1×10^{-3} Torr.

Initially the device was tested in the 10^{-7} Torr pressure region as a conventional traveling-wave tube using the coupled helix couplers and the short sections of helical slow-wave structures. An electronic gain as high as 35 db was observed near 2 GHz. For some input frequencies, harmonics as high as the fourth could be detected. It was found that for those pressures at which the plasma could be generated by a hot-cathode discharge most easily (high 10^{-3} Torr region), the beam cathode emission dropped off rapidly. However, it was possible to maintain a beam-generated plasma in the 10^{-4} Torr region. Under these conditions, unfortunately, the density of the plasma was not correct for optimum coupling to the elliptic-cavity couplers. It appears necessary to optimize the pressure and hence the plasma density for best coupling on the one hand and best beam-plasma interaction on the other hand. In addition, some changes in the gap width of the elliptic-cavity couplers may be needed in order to strike a better compromise between the above criteria.

Further testing is scheduled for the coming period. Detailed harmonic power measurements will be made on the beam-generated plasma as well as the hot-cathode discharge plasma. The various parameters optimizing the elliptic-cavity coupling method will be studied. Digital computer results on the saturation characteristics and the harmonic current generation will be obtained from the nonlinear, large-signal equations.

8. Paramagnetic Materials for Millimeter- and Submillimeter-Wave Detection

Supervisor: G. I. Haddad

Staff: C. F. Krumm

The purpose of this phase of the program is to investigate the feasibility of using paramagnetic materials to detect millimeter- and submillimeter-wave radiation. Currently, a downconversion scheme is being investigated. It is similar in principle to a three-level maser except that the roles of the pump and signal powers are reversed, i.e., the signal frequency, ν_{13}, is higher than the pumping frequency, ν_{12}. The presence of high-frequency power is detected by noting the changes it produces in the low-frequency reflection coefficient.

This type of device is essentially a narrow-band detector whose center frequency is determined by the energy separation of Levels 1 and 3. By choosing a paramagnetic material with appropriate zero-field splittings, it should be possible to operate this detector at almost any microwave through submillimeter-wave frequency.

The internal conversion loss (loss inherent in the detection process) for this scheme may be arrived at most simply by using the Manley-Rowe relations as derived by Wiess[1]. Use of this method shows that the conversion loss is ν_{12}/ν_{13}. Comparison of this loss with the losses of other currently available detection methods shows that the downconversion scheme becomes increasingly advantageous as the operating

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[1] Wiess, M. T., "Quantum Derivation of Energy Relations Analogus to those for Non-linear Reactances," Proc. IRE, vol. 45, No. 7, pp. 1012-1013; July, 1957.

frequency is increased. We have presented theoretical considerations of this scheme in detail elsewhere[2,3].

An experimental apparatus for testing the detection scheme has been designed and constructed. The material to be used in these experiments is iron-doped rutile. The ground state of this material has a spin of 5/2 and is split into three sets of doublets. Only the three lowest lying levels will be used in the first experiment. For Levels 1 and 3 this makes the zero-field splitting 43.3 GHz. Initial experiments will be performed near 35 GHz. Experiments at higher frequencies are planned at a later date. The first tests at liquid helium temperatures will be performed in the next few weeks.

In addition to the experimental work, a theoretical study of this device is being performed. One phase of this analysis involves a consideration of temperature effects in the detection process. On the basis of the similarity of this device to a maser amplifier one would think that operation would be possible only at liquid helium temperatures. This point is currently being investigated.

This device can be regarded as a millimeter-wave-microwave circuit element or frequency converter. If this point of view is used, then it is pertinent to develop a description of the device in terms of externally measurable device parameters. Once these parameters are obtained experimentally the theoretical description should permit the evaluation of other interesting device parameters, e.g., minimum

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2. Krumm, C. F. and Haddad, G. I., "Millimeter- and Submillimeter-Wave Quantum Detectors," Proc. IEEE, vol. 54, No. 4, pp. 627-632; April, 1966.

3. Krumm, C. F. and Haddad, G. I., "Quantum Detectors," Proc. Sixth Int. Symp. Microwave and Optical Generation and Amplification, Cambridge, England; September, 1966.

detectable power. Consequently, an analysis of the device, using its microwave and millimeter-wave circuit characteristics, has been started.

In view of the fact that other detection and frequency conversion schemes using paramagnetic materials have been proposed[4,5] it seems appropriate to compare these with the presently considered scheme in order to evaluate their relative sensitivity. Some theoretical work in this area is also currently in progress.

9. Bulk Semiconductor Materials for Millimeter- and Submillimeter-Wave Detectors

Supervisor: G. I. Haddad

Staff: I. Eldumiati

The main purpose of this phase of the program is to investigate bulk semiconductor materials for millimeter- and submillimeter-wave detection. The photoconductive properties of the material will be employed for this purpose; however, the change in conductivity will be monitored at a microwave frequency, rather than d-c. Photoconductive

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[4] Fontana, J. et al., "Harmonic Generation by Means of Multiple Quantum Transitions," Advances in Quantum Electronics, J. R. Singer, Ed., Columbia Univ. Press, New York, pp. 612-618; 1961.

[5] Anderson, P. W., "The Reaction-Field and Its Use in Some Solid State Amplifiers," Jour. Appl. Phys., vol. 28, No. 7, pp. 1049-1053; July, 1957.

detectors using d-c bias have been described[1,2]. The response time of such detectors is limited by the circuit resistance and distributed capacitance, and the detectivity is limited by the contact noise and the noise in the post amplifier.

It has been shown[3-5] that high-frequency biased photoconductive detectors are better than the d-c biased ones both in response time and detectivity.

The basic elements of the detection scheme are shown in Fig. 9.1, and they consist of the following:

1. A cavity containing the semiconductor material,
2. A local oscillator at a microwave frequency which is coupled to the cavity through a circulator,
3. A low-noise amplifier and a conventional detector and
4. A coupling hole for the high-frequency signal to be detected.

If the semiconductor material has an energy-band structure as shown in Fig. 9.2, then with the material cooled to a low temperature all

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1. Putly, E. H., "InSb Photoconductive Detector," <u>Appl. Optics</u>, vol. 4, No. 6, pp. 649-656; June, 1965.

2. Giggy, G. F. et al., "Photoelectric Millimeter-Wave Detectors," Final Report, Raytheon Co., Contract No. AF30(602)-3015, Burlington, Mass.; June, 1964.

3. Sommers, H. S., "Demodulation of Low-Level Broad-Band Optical Signals with Semiconductors," <u>Proc. IEEE</u>, vol. 51, No. 1, pp. 140-146; January, 1963.

4. Sommers, H. S. and Teutsch, W. B., "Demodulation of Low-Level Broad Band Optical Signals with Semiconductors: Part II--Analysis of the Photoconductive Detector," <u>Proc. IEEE</u>, vol. 52, No. 2, pp. 144-153; February, 1964.

5. Sommers, H. S. and Gatchell, E. K., "Demodulation of Low-Level Broad-Band Optical Signals with Semiconductors," <u>Proc. IEEE</u>, vol. 54, No. 11, pp. 1553-1568; November, 1966.

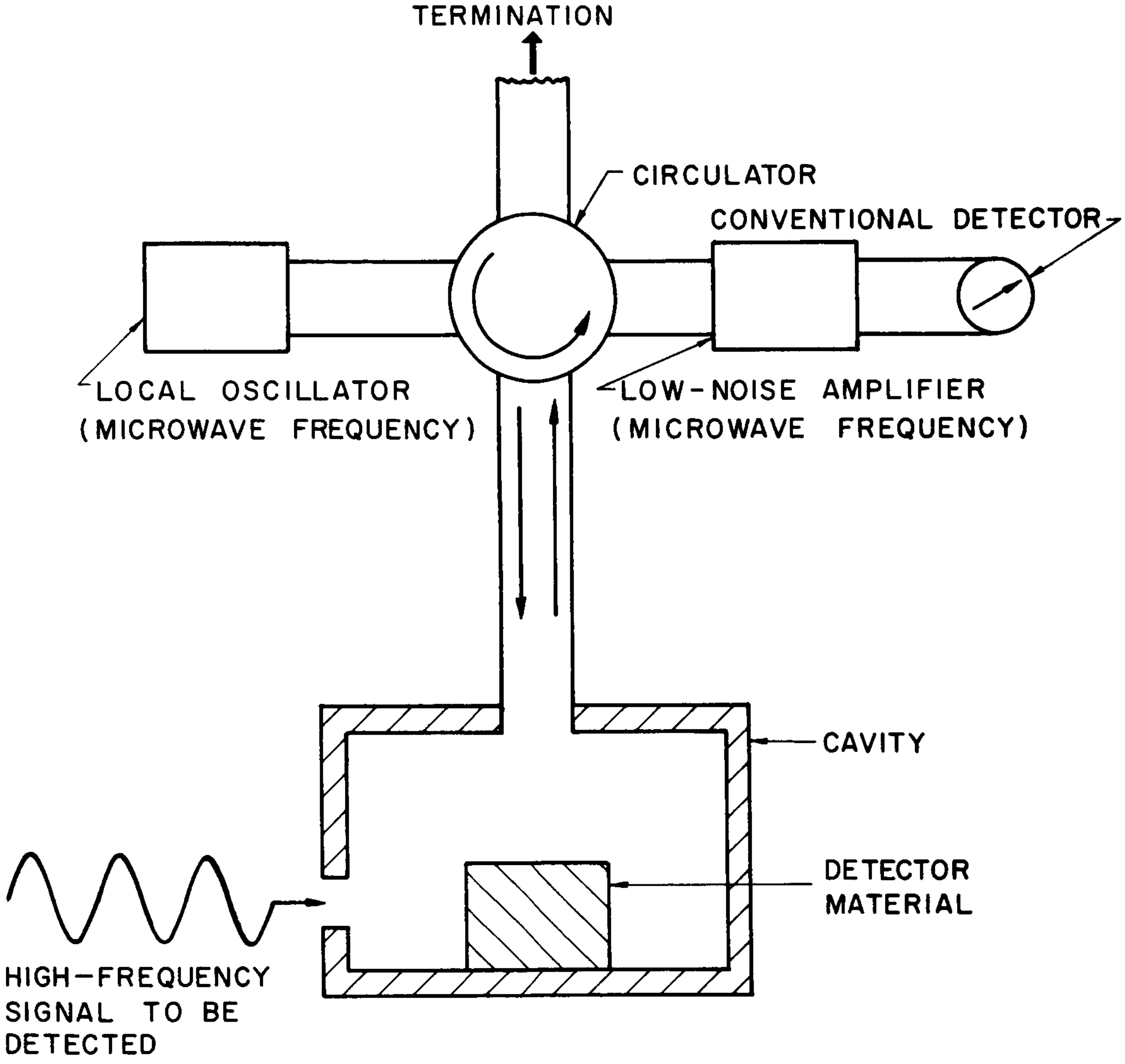

FIG. 9.1 PROPOSED HIGH-FREQUENCY DETECTION SCHEME.

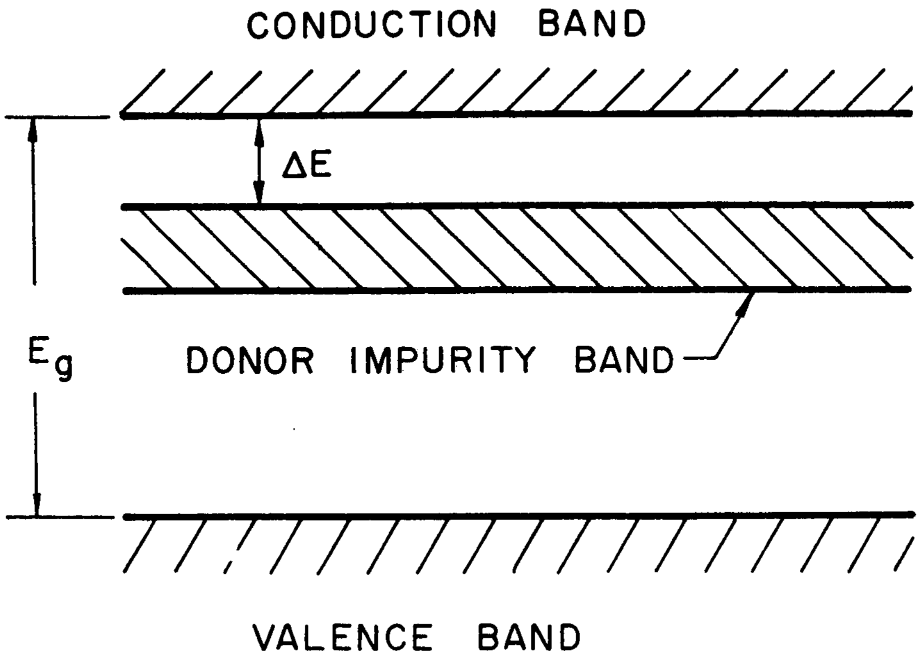

FIG. 9.2 ENERGY-BAND PICTURE OF A SEMICONDUCTOR MATERIAL FOR USE IN THE PROPOSED DETECTION SCHEME.

the electrons will reside in the valence and impurity bands. If the frequency of the local oscillator is such that $f_{\ell_o} < \Delta E/h$ (h is Planck's constant), the material behaves as a dielectric, and the coupling coefficient of the local oscillator to the cavity can be adjusted to the desired value of reflected power. However, if the signal to be detected is such that $f_s > \Delta E/h$, the electric properties of the material will change, which in turn will cause a change in the reflected power and can be detected by a conventional detector.

In order for the semiconductor material to respond to millimeter-wave radiation, the energy separation between the impurity and conduction bands must be on the order of 10^{-3} eV. InSb is an appropriate material for this purpose and usually a magnetic field is required to separate the impurity and conduction bands[6,7].

In order to determine the characteristics of this detection scheme, a detailed evaluation of the properties of the material at millimeter-wavelengths and microwave frequencies in the presence of d-c electric and magnetic field is required. It is anticipated that the results of the study will be useful not only in evaluating the proposed detection scheme but also in other possible applications of bulk semiconductors such as limiters, switches and others. Mixing in bulk semiconductors will also be investigated for utilization in superheterodyne-type detection.

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[6] Yafet, Y. et al., "Hydrogen Atoms in a Strong Magnetic Field," Jour. Phys. Chem. Solids, vol. 1, No. 3, pp. 137-142; November, 1956.

[7] Sladek, R. J., "Magnetically Induced Banding in InSb," Jour. Phys. Chem. Solids, vol. 5, No. 3, pp. 157-170; May, 1958.

An experimental apparatus has been designed and constructed in order to measure the properties of semiconductor materials for these various applications. We are presently investigating the properties of InSb.