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Study of Unique Detection Techniques

Contract AF 33(616)-6849
Task Number 62821

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Department of ELECTRICAL ENGINEERING

THE OHIO STATE UNIVERSITY
RESEARCH FOUNDATION
Columbus Ohio

REPORT

by

THE OHIO STATE UNIVERSITY RESEARCH FOUNDATION
COLUMBUS 12, OHIO

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ABSTRACT

Detectors of "action at a distance" phenomena are considered with special attention given to biologic detectors. Emphasis is on sensitivity and representative detectors are compared in terms of quantum efficiency. Two experimental detectors are described and other detection schemes are suggested. Superregeneration is extended to the D.C. care where it is compared with the behavior of nerve membrane. It is concluded that detectors based on quantum mechanical principles offer the ultimate in sensitivity and frequency range while detectors based on neurophysiological schemes offer the ultimate in small size and high gain.

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STUDY OF UNIQUE DETECTION TECHNIQUES

I. INTRODUCTION

Detection is defined as the finding out, or discovery, of what was concealed. In this study the purpose is to investigate new detectors or detection techniques for surveillance applications. Because surveillance generally implies detection some distance, this study has been restricted to those emanations involving the "action at a distance" principle. These include:

Emanations	Quantities to be detected
Electromagnetic Radiation	Intensity
Gravitational Radiation	Spectral composition
Acoustic Waves	Spatial composition
Particle or Vapor Emission	Polarization
	Velocity range
	Chemical composition

Detectors	Detection methods
Electrical	Continuous/discontinuous
Chemical	Active/passive
Biological	
Mechanical	

Some of the emanations listed may be interdependent. For example it is possible, in theory at least, to detect the presence of contaminating particles in the atmosphere by their selective absorption of electromagnetic radiation. On the other hand, the dependence of gravitational radiation on electromagnetic radiation is unknown. The only known gravitational fields have insignificant time-varying components, but there is a faint possibility that gravitational waves can be generated in much the same way as electromagnetic waves provided that gravitational fields propagate at a finite velocity.* Acoustic waves are those waves which propagate in elastic media, including such disturbances as sound waves, seismic waves, and bomb blast disturbances. It is possible to detect these waves by electromagnetic means through the changes in ionization potential despite the

* See Sec. III A.

fact that the better detectors use mechanical motion as an intermediate step in the detection of these waves.

In considering the quantities to be detected, the intensity is of paramount importance thus, in this study it is taken as the primary criterion of successful detectors. That is, whether a detector is of any value or not depends primarily on the revelation of the hidden emanation. The ability of the detector to make spatial and temporal correlations is of only secondary importance. Because of the fundamental nature of electromagnetic radiation and also the recent successes in devising sensitive detectors for it, an effort is made to study the theoretical limit of detectability in the electromagnetic spectrum in terms of the quantum nature of radiation. The classification of the types of detectors listed is also quite arbitrary. For example the diode is considered as an electrical detector of electromagnetic fields, yet the force on the electrons in the space between anode and cathode is mechanical. Perhaps a better example would be the nerve tissue which normally is considered as a basic element of biological detectors. Here a thin membrane, selectively permeable to the ions of the solutions in which it is immersed, maintains a polarizing voltage which depends on the relative ion concentrations on either side. To initiate a local response (i.e., nerve impulse), the ionic concentration at a single point is altered in such a way that the membrane abruptly switches polarization direction from (-) to (+) on the interior of the membrane, so that the disturbance travels along the nerve fiber. Although this scheme is common to all animals in nature, it cannot properly be called either a mechanical, a chemical, or an electrical detector even though all of these stimuli can trigger the local response through a change in the ionic concentration. In this way all of the senses except vision can be explained --- for vision an additional photochemical reaction is involved with a sensitivity so high that the quantum detection probability at the retina approaches one in five.(1)

After many different methods of detection are examined, it becomes apparent that a given detection system such as a sonar system or a microwave radiometer involves long chains of detectors, but only a small number of general detection methods. For example, the scintillation counter detects single primary events by converting them to light flashes; a second detector converts the light flashes to pulses of free electrons; these electrons are detected by a secondary emission multiplier used as an amplifier, the resulting current pulses are then detected by a galvanometer, counter, oscilloscope, or pulse analyzer, each of which contain chains of detectors and each of which is only a link in the chain between the original stimulus and the human who is trying to detect it. These detection methods are based on only two classifications: (1) whether the input/output function is continuous or intermittent, and (4) whether or not an auxiliary source of energy is required.

The foregoing is an outline of the items considered in this study. During the first year of this contract the research efforts has been evenly divided between the study of present detection techniques with associated physical phenomena, and the construction of experimental detectors. Biological detection techniques as well as physical phenomena such as Cerenkov Radiation[2] and the Mossbauer Effect[3] were investigated because of the possibility that they might be applied in new detectors. These studies suggested a series of ideas for new detectors, as well as improvements to be made in detectors presently used. In addition, the chart in Fig. 1 was devised as a quick way of comparing individual detectors. Of the new detectors suggested, two were chosen as being especially interesting for reconnaissance applications. The microwave optical detector was chosen for its potential ultimate sensitivity in the millicrowave region as one form of the atomic detection, and the microwave mechanical detector for its uniqueness and simplicity.

Finally, while nerve membrane has the possibility of being a nearly ideal detection material for surveillance applications, the difficulties in maintaining the required enviornment and extracting its output prevent its direct application at present. Although some exceptional nerve preparations have been kept alive longer than four hours the preparation process is so critical that no accurate predictions of the lifetime can be made. The difficulty in making electrical connection with nerve tissue can be appreciated where it is realized that the thickness of nerve tissue is measured in hundreds of Angstrom units (10^{-10} meter), and that recording electrodes are generally measured in units of 10^{-6} meter in diameter while the currents are near 10^{-14} amperes or less.[4,5] One solution would be to develop a synthetic material with the negative resistance characteristics of nerve membranes, but without the strict requirements on enviornment. Perhaps a solution already exists in combining the negative resistance characteristics of presently available semi-conducting elements with the small size of "molecular" electronics circuits. Such a combination would require control only over temperature and electrical power, but might lead to some nasty problems of interaction between neighboring detectors.

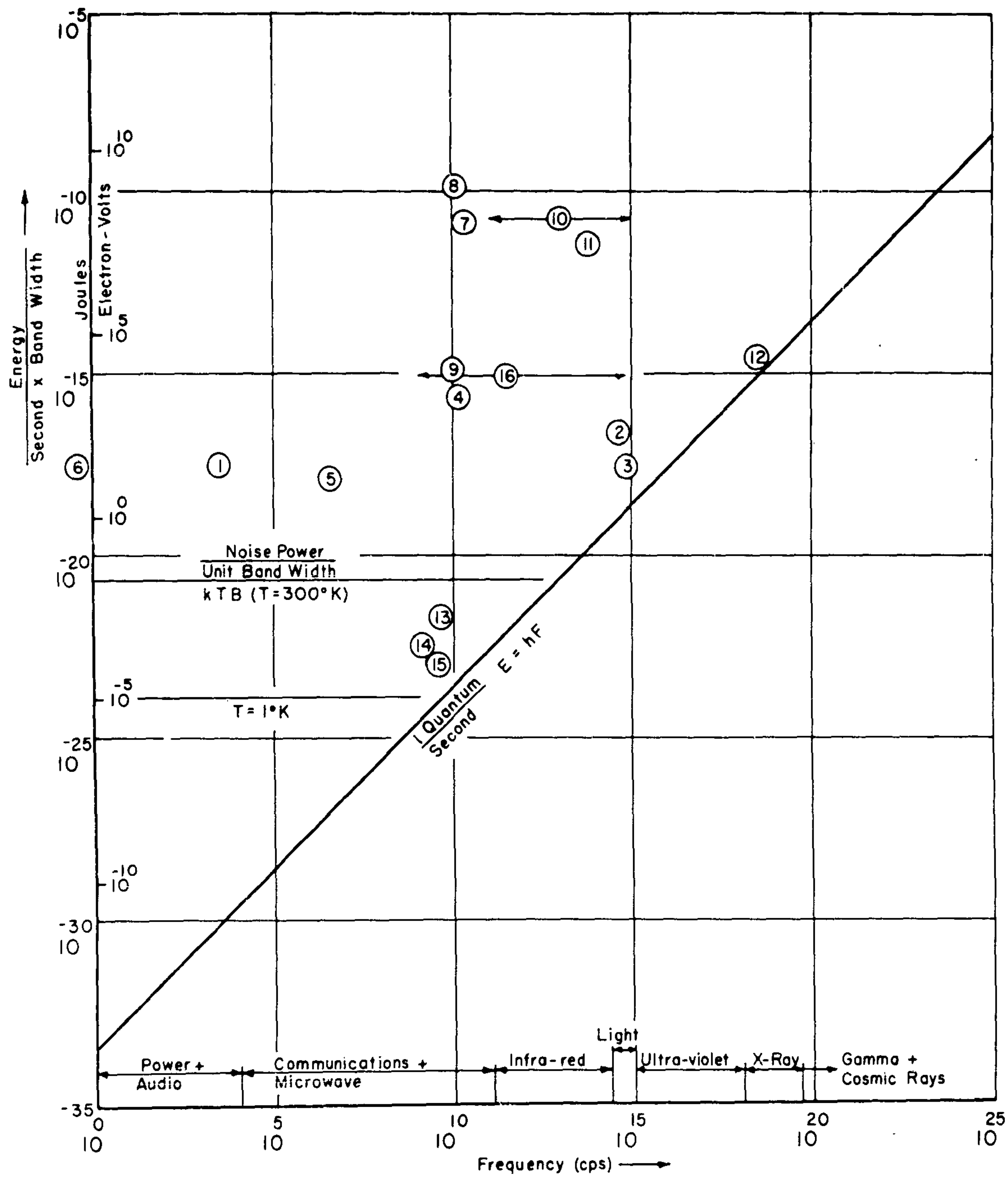

Fig. 1. Frequency vs. Minimum Detectable Energy For Detectors of E-M Radiation.

TABLE I

Data Points for Map of Detector Sensitivity vs. Frequency

(1) Human ear operating at 2500 cps. Best reported sensitivity, 5×10^{-17} watt (from Stevens and Davis, Hearing, Wiley (1938), pp. 344-345). Information on bandwidth (from O. Glasser, ed., Medical Physics vol. 2, Yearbook Publishers (1950), p. 1002): lowest pulse rate of action potential in auditory nerve of cat was 24 cps for an input of 2600 cps. Bandwidth taken as 1/2 of sampling frequency.

(2) Human eye - - - "energy for visual excitation has repeatedly yielded results of the order of 100 quanta (variation from 58 to 148) using blue-green light (5000 Å)." Due to scattering and losses in the eye the "actual effective number is 5-14" (from O. Glasser, ed., Medical Physics, Yearbook Publishers (1950), p. 1659, vol. 1).

(3) Photomultiplier photocathode efficiency approaches 10^{-1} (according to Condon and Odishaw, Handbook of Physics, McGraw Hill (1958), p. 8-66); ---"photocathode efficiency of about 1/20 electron per photon" (Sproull, Modern Physics, Wiley (1956), p. 449).

(4) Microwave coherent detector using a continously rotating phase shifter. (D. Yaw, A K-band Superhetrodyne System Using a Rotating-Guide Phase Shifter, Report 444-19 Antenna Laboratory Dept. of Electrical Engineering, The Ohio State University Research Foundation, 15 February 1955, describes a system with a max expected sensitivity of -150 dbw at 25 kmc with a 4 cps bandwidth.

(5) Ionospheric Scatter Propagation Receiver operated at 49.8 mc with indicated bandwidth of 100 cps is able to detect 1/10 μ volt across 52-ohm load. System uses noise cancellation technique. (Ta-Shing Chu, Ionospheric Scatter Propagation at Large Scatter Angles, Antenna Laboratory Dept. of Electrical Engineering, The Ohio State University Research Foundation, 1 July 1957).

(6) Chopper-stabilized DC amplifier--Hewlett-Packard Model 425A can detect better than 1 μV across 1 megohm at frequencies below 0.2 cps using optical chopping system.

(7), (8), (9) Obtained from reference (4). (7) is for 1N26 crystal rectifier operated at 25 kmc followed by a 1000-cps amplifier with a 4-cps bandwidth. Sensitivity of -100 dbw is reported. (8) Barretter operating at 10 kmc followed by 1000-cps amplifier whose bandwidth is 4 cps giving a 90 dbw sensitivity using Type 614 bolometer. (9) Synchronous detection using a hybrid tee and a narrow-band audio amplifier with a 4-cps band-pass gave -144 dbw.

(10) Golay detector sensitivity 6×10^{-11} watts RMS Equivalent Noise Input. Time constant 1.6 sec, flat from microwave to ultra-violet (advertisment from Proc. IRE 47, 9 p. 64A, September 1959 for Eppley Laboratories Inc., Newport R. I.)

(11) PbTe detector of 4.3 microns, 7×10^{-12} watts. S/N ratio unity (?) operated at 77°K. 1-cps bandwidth at 800 cps (advertisment in Proc. IRE 47, 9 p. 53A September 1959 for Honeywell Military Products Group Hopkins, Minnesota)

(12) J. Taylor and W. Parrish, "Aborption and Counting Efficiency Data for X-ray Detectors," Rev. Sci. Inst. vol. 26 #24 p. 367-373 April 1955, present data on relative efficiency of G-M proportional, and scintillation counters showing that scintillation counters are best detectors of X-rays with 90% to 99% efficiency.

(13) M. Uenohara and W. M. Sharpless, "An Extremely Low-Noise 6-Kmc Parametric Amplifier Using Point-Contact Diodes," Proc. IRE, 47 p. 2114-2115: The device noise figure measured at 90° K for double-sideband operation was 0.3 db, which represents an excess noise figure of 21° K.

(14) Arams and Okwit, "Packaged Tunable L-band Maser System" Proc. IRE 48 p. 866-874: ruby maser operated at 1.5° K ------system noise factor of 0.5 db corresponds to 35° K.

(15) DeGrasse, R. W., and Scovil, H.E.D., "Noise Temperature Measurement on a Traveling Wave Maser," Appl. Phys. 31, p. 443; average system noise temperature over 37 measurements in 30 minutes was 10.7° K at 5.815 Kmc.

(16) Lelevie, Bogljub, "Criteric For Choice of a Superconducting Bolometer" p.1234, Appl. Phys. 31, July 1960: "--possible to measure down to 10^{-15} watt using superconducting bolometer controlled to 10^{-5} degree."

II. Theoretical Limits of Detectability

In the graph shown in Fig. 1 an attempt is made to assess the sensitivity of presently known detectors in terms of a theoretical standard. By comparing the minimum detectable energy per unit bandwidth per second with the power represented by one quantum per second per unit bandwidth, a measure of the quantum efficiency may be obtained. The addition of a frequency scale for the abcissa provides a two-dimensional map on which each detector can be plotted as a point or as a line. From this map it can be seen that few detectors approach the limiting sensitivity of one quantum / second; and of those that do, only the maser and the parametric amplifier provide any great improvement in energy sensitivity over previous detectors. In the range between 10^{10} and 10^{14} cps there is an obvious gap for which there are now no sensitive detectors, although the recent application of an avalanche diode cooled to liquid nitrogen temperatures has been reported as a possible detector of individual infrared photos.[6] Potentically, those detectors such as the maser, and the atomic devices which utilize quantum-mechanical techniques, can fill this gap. In general, this class of detectors[7] appears to be the ultimate as far as sensitivity is concerned. One reason for this is that these detectors depend on discrete quantum-mechanical interactions, while electronic detectors involve macroscopic interactions between large numbers of quanta and large numbers of electrons.

III. Experimental Detectors

A. Microwave/Optical Detector

The schematic arrangement of this detector is shown in Fig. 2 and a photograph of the apparatus is shown in Fig. 2 A. It was adapted from the method used by Daniels[8,9,10] and his coworkers at The University of British Columbia for the measurement of the spin lattice relaxation time in neodymium ethylsulphate. The physical principle involves the change in Faraday rotation for light with changes in the average magnetic moment of the crystal. The average magnetic moment, in turn, depends on the density of paramagnetic ion in the crystal, the external magnetic field intensity, the spin temperature, and the microwave energy absorbed by the crystal through paramagnetic resonance. This device is of interest primarily because it is fundamentally an atomic detector different from any detector previously studied.

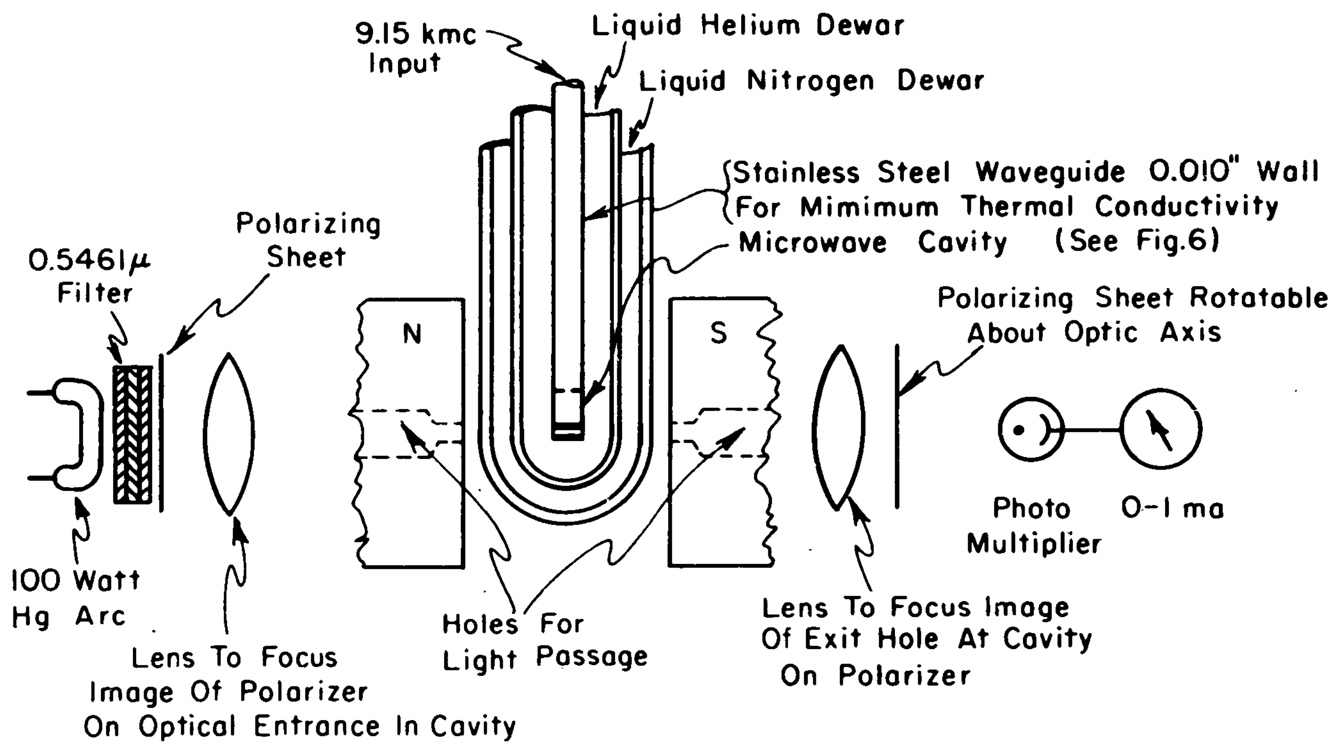

Fig. 2. Microwave Optical Detector
(Schematic Arrangement)

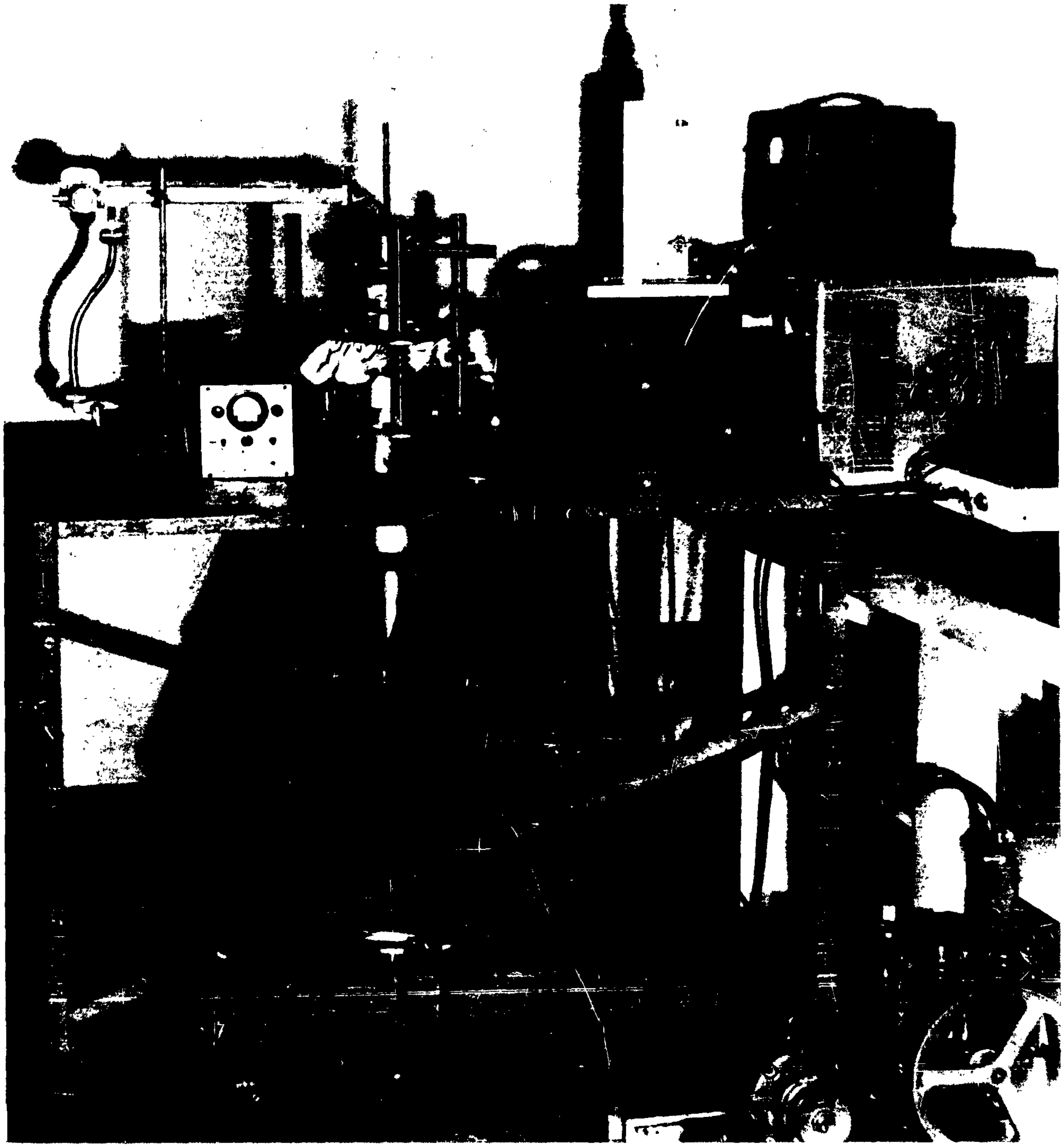

Fig. 2A. Microwave/Optical Detector

Like all the quantum electron devices proposed, it has the potential of being a very sensitive detector in the millimicrowave region. Furthermore, the understanding of such a detector may lead to other types of atomic detectors which will approach the sensitivity of one quantum/second in Fig. 1. No macroscopic device will be able to reach such a high sensitivity because they depend upon the average properties of a uniform number of quanta. An analysis of this detector is presented in Appendix I.

This detector (Fig. 2) can be considered as the combination of an optical polarizing microscope and on electron paramagnetic resonance spectrometer linked together by the crystal. The polarizing microscope or polarimeter consists of a mercury arc lamp with a green line filter (0.546 μ) as the source, and a photomultiplier as the detector. Two polaroid discs are used as the polarizing material. The two lenses serve to focus between the polarizing planes and the optically active crystal. The paramagnetic spectrometer consists of an external magnetic field (up to 0.8 weber/m^2) surrounding a double dewar flask containing liquid nitrogen and liquid helium respectively, with the flask in turn enclosing a microwave cavity tuned to 9.16 Kmc (see Fig. 6). A single crystal of the paramagnetic salt (neodymium ethylsulphate) is glued to the end of the cavity at the point of $H_{R.F.\ max}$ with its optic axis parallel to the H_{dc}. This assembly is then placed so that the crystal lies in the optical path of the polarimeter with the light passing through holes in the magnet and cavity and through the unsilvered portions of the dewars.

In operation the current through the magnet is adjusted for minimum microwave reflection from the cavity (i.e., paramagnetic resonance) using the circuits of Figs. 3 and 5. (For a frequency-modulated system, a display similar to Fig. 4B can be obtained with an oscilloscope). This condition provides paramagnetic absorption of the microwave radiation by the crystal, and the detector output can then be determined by the microwave power vs. polarization angle characteristic, or by the change in photocurrent vs. small microwave signals using fixed polarizers as analyzed in Appendix I.

No data on sensitivity have been obtained at this time; the polarimeter is under construction. Furthermore, no large perfect single crystals are available, although many small crystals have been grown. It is expected that this problem will be solved with the establishment of more refined crystal-growning techniques. In order to test for paramagnetic resonance, a small imperfect 100%

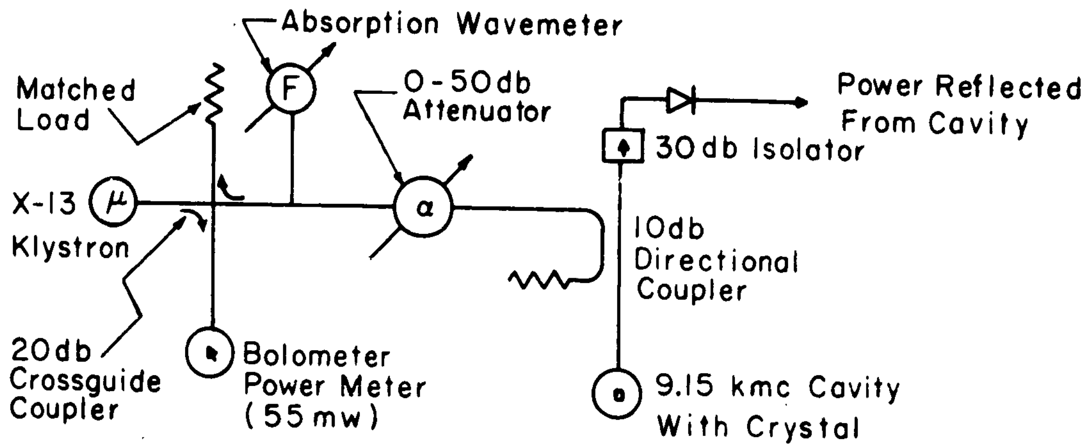

Fig. 3. Microwave Optical Detector
(Microwave Circuit)

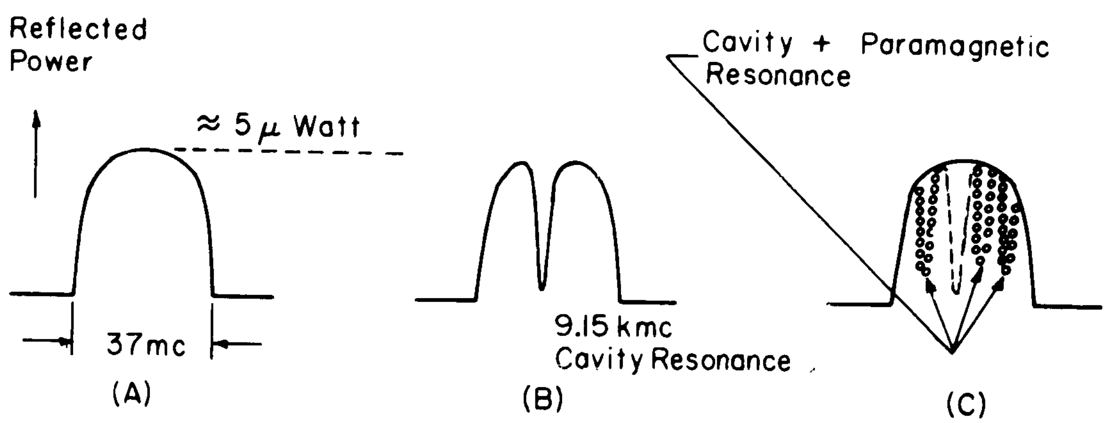

Fig. 4. Paramagnetic Resonance Experiment

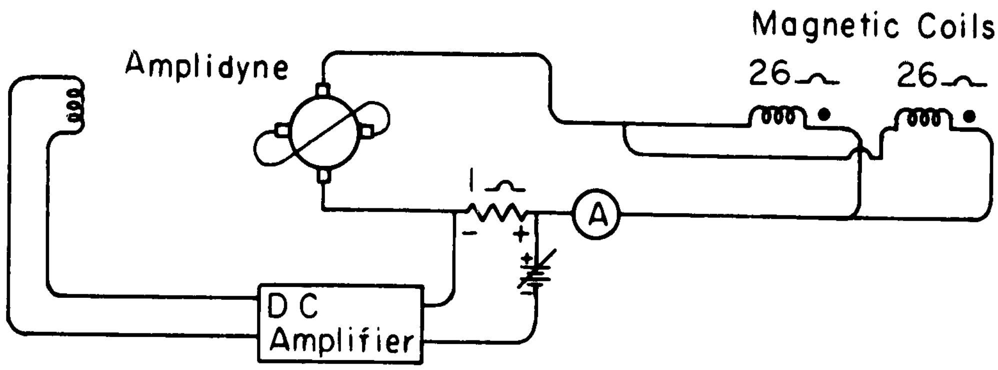

Fig. 5. Microwave Optical Detector-Magnet Power Supply

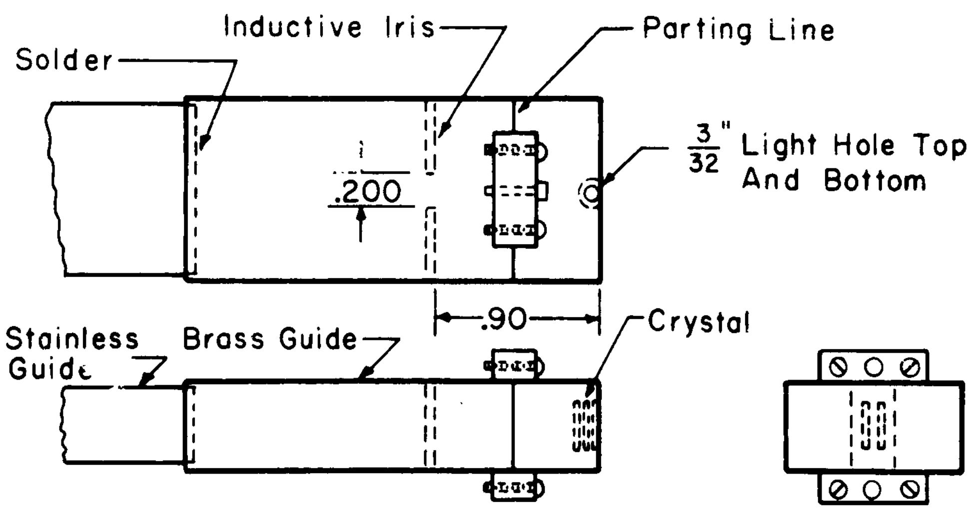

Fig. 6. Microwave Optical Detector
(Microwave Cavity)

concentration crystal of Neodymium ethylsulphate was used. After cooling the dewars the microwave circuit was arranged to give the display shown in Fig. 4 B. Adjustment of the magnet current between 2 and 5 amperes caused several large changes in both position and amplitude of the cavity absorption line. There effects are indicated in Fig. 4C. No saturation could be detected even with power levels up to 5×10^{-5} watt. Both of these effects, the lack of a single sharp absorption line and failure to saturate, indicate that the paramagnetic ions in the crystal should be diluted and that the initial crystal may have a polycrystalline structure. It is estimated from the weight of the crystal that there are approximately 10^{-22} spins in this crystal. It is expected that these problems will be solved in the near future, and that improvements can be made to establish the following properties during the coming year.

(a) The sensitivity and the noise figure of this microwave optical detector
(b) The discovery of a better material
(c) The exact nature of the interactions between the microwave fields and the optical fields, so that this detector can be generalized to include milli-microwave frequencies and other new schemes of quantum detection.

III. B. Microwave/Mechanical Detector

This detector is included more for its uniqueness than for any advance in sensitivity. A sketch of this detector is shown in Fig. 7. The microwave energy entering the detector is propagated in the TE_{10} mode so that the E-field is parallel to the b dimension of the guide. By enclosing the end of the guide in a cavity the electric field is multiplied by the Q of the cavity. The Coulomb force due to this electric field then distorts the piezo-electric wall of the cavity, and the voltage between the piezo-electric plates becomes a measure of the microwave power. Assuming a rigid cavity the total force on the cavity face for this type of detector is Eq. (1)

(1) $F = QP/2\omega b$

where Q is Q of the microwave cavity (unloaded),
P microwave power entering the cavity,
ω microwave frequency in rad/sec, and
b guide dimension parallel to electric field.

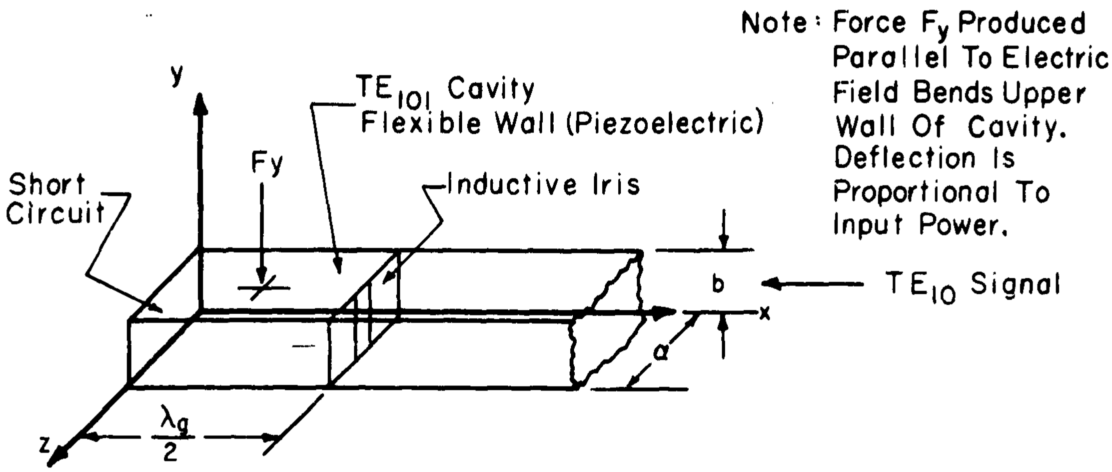

Fig. 7. Microwave Mechanical Detector

Using standard 1 x $\frac{1}{2}$ - inch guide at 10 Kmc with 1 mw power and a cavity Q of 10^4, the total force is 8 x 10^{-9} nts. Although this force is quite small and difficult to detect, it can be detected if it is varied at a periodic rate in resonance with the piezoelectric plate. This can be accomplished by modulating the incident microwave energy at the resonant frequency of the piezoelectric crystal. In this scheme the movement of the crystal causes only second-order detuning of the cavity since its movement is parallel to the noncritical dimension of the cavity. The one flaw apparent at this time is that the original effect was detected acoustically by the sound coming from a sheet of aluminum foil, replacing the piezoelectric resonator. This sound varied in pitch with the modulation frequency of the source klystron. This means that while the aluminum foil could bend in two dimensions into a compound curve, a piezoelectric crystal may not be able to bend in this fashion and still maintain a high Q. Assuming that this will present no serious problem and that at least half of the energy entering the cavity can be coupled out of the crystal, then by present techniques it should be possible to detect amplitude-modulated signals down to 10^{-17} watt. This would represent an improvement over the conventional microwave superhetrodyne receivers by a factor of ef 10 to 1000 in sensitivity.

This detector is the result of an effort to detect microwave fields by mechanical means. Although two other devices with similar properties have been reported,[11,12] neither appears to have the ultimate sensitivity and ruggedness of this detector. One objection is that the microwave field must be modulated at the resonant frequency of the crystal which might prevent its application in pulse reception. Finally, this device is interesting because it behaves as an energy transformer between the microwave field and the piezoelectric field.

IV. Other Suggested Detection Schemes

A. Gravitational Dipole

It has been suggested that if gravitational waves could be generated, they would propagate through all known materials, even through the earth. Figure 8 represents one scheme which might produce such radiation. In this scheme a magnetostrictive bar is excited in the longitudinal mode at its fundamental frequency. If the bar moves at the proper rate, a mass detector located on the axis of the bar at some distance from the center will see not only a stationary mass point, but also one oscillating in position at the frequency of excitation of the bar. Two assumptions are implicit in this scheme; these are (1) that such radiation would propagate at a finite velocity, and (2) that the newtonian concepts employed are valid for these conditions. Such a source would probably require a bar oscillating at the highest possible frequency and amplitude. Walenta and Conners [13] at the Jet Propulsion Laboratory, report the operation of magnetostrictive bars at 5000 g and 20 Kc for the calibration of accelerometers.

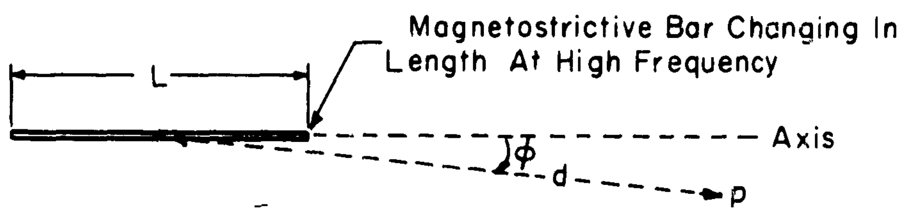

Fig. 8. Gravitational Dipole

B. Thermoluminescent X- and Y- Radiation Detector

In Fig. 9 a scheme is presented for the periodic measurement of accumulated X- and γ- radiation as suggested by Winans and Seldin [15]. In this detector the total photons emitted from the thermoluminescent material during the heating phase are proportional to the integrated X- and γ- radiation received in the interval since the material was last heated. This detector is of interest because it

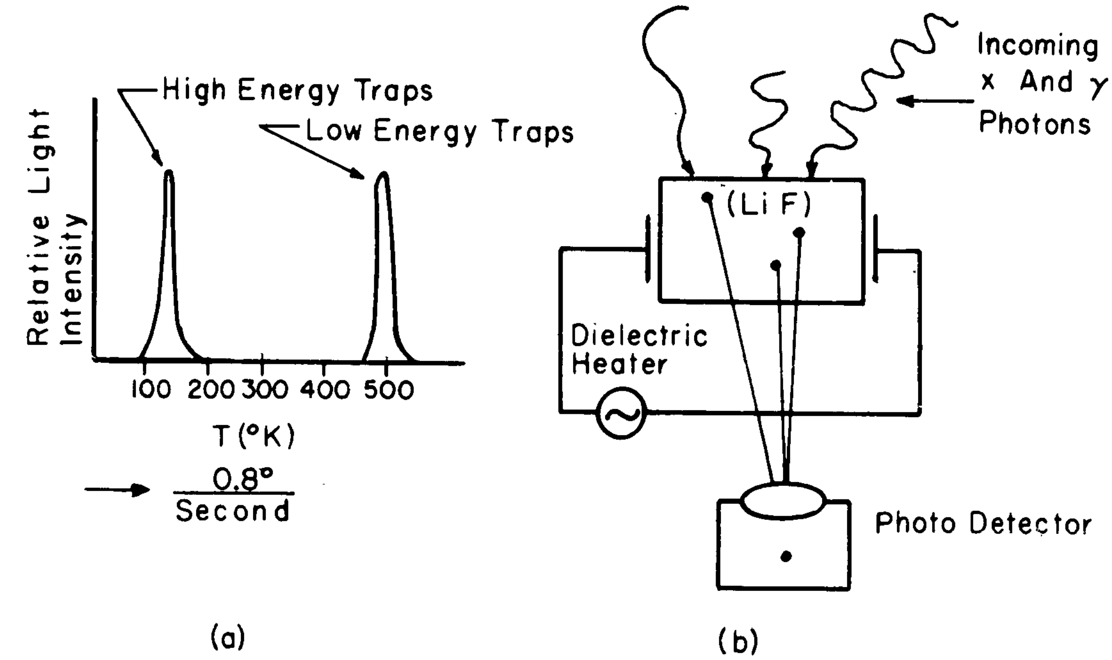

Fig. 9. Thermoluminescent Detector of X-rays.

provides a potential method of detecting nuclear explosions in an area covered only by a satellite. Its advantage over film dosimeters is that it can be reused repeatedly, and its advantage over more conventional detectors is that power is required only when readout is desired. Such a device is now under development at The Naval Research Laboratory, Washington, D. C., for use as a personnel dosimeter. [16]

C. Microwave String Galvanometer

This scheme Fig. 10 represents an initial attempt to obtain mechanical forces from microwave fields. The essential idea is that the deflection of the mirror depends on the energy stored in the string by torsion. This energy can be as low as 10^{-16} watt in commercial D' Arsonval galvanometer so that if the circularly polarized wave incident on the dielectric plug can be made to convert half of its energy into torque, it is reasonable to expect similar senstivity for this device. Of the two other known devices using torsion effects resulting from microwave fields,[11,12] neither is very sensitive ($\approx$ 100 mw minimum), although both are two-port devices designed for minimum VSWR. This device is of interest because it is a passive detector with the possibility of moderate sensitivity which could be operated in the submillimeter region. It is perhaps too fragile for a reconnaissance vehicle, but its deflection angle should be linearly related to power, making it useful as a laboratory instrument.

D. Secondary Emission Amplifier

This scheme uses the fact that the dynodes of a secondary-emission multiplier have negative resistance characteristics as a result of the secondary-emission process. Since negative resistance can be used to cancel part of the resistance in a tuned circuit, and since these multipliers have current gains of over 10^6, it appears that they would be useful as tuned amplifiers. The strongest objection to this is that these devices are relatively noisy and therefore could not be used for small signals. Alternatively, operation as a video amplifier, as suggested in Fig. 11, could provide advantages over a conventional RC-coupled vacuum tube amplifier in that the negative resistance tends to minimize the effect of shunt capacitance.

E. Detectors based on Physiological Methods

1. Electrical Analogue of Single Cells in Limulus Eye.

The work by Hartline at the University of Chicago to Rockfeller Institute on the eye of the horseshoe crab (Limulus) shows clearly the analogue-to-digital nature of biological detectors[19]. When a single nerve fiber was combed out of the optic nerve bundle and connected to a recording oscillograph, constant-amplitude pluses were obtained of approximately 80 mv.

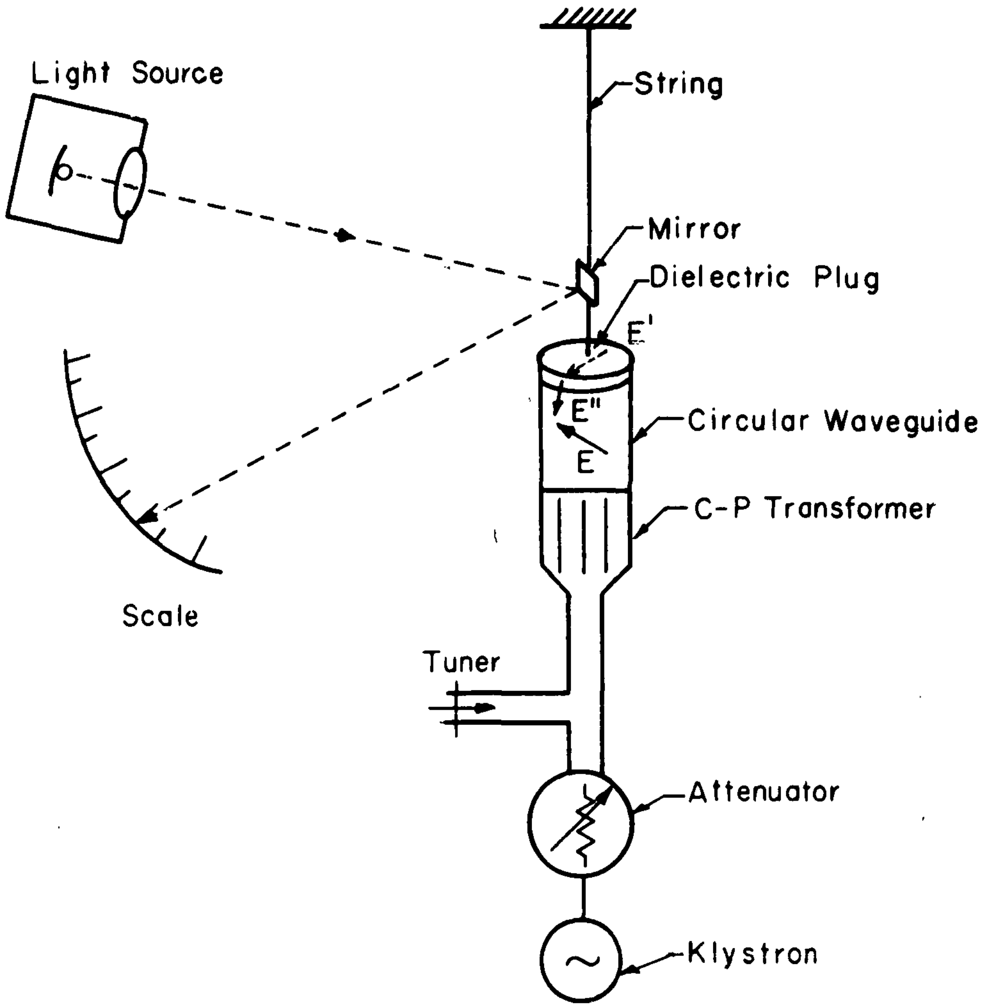

Fig. 10. String Galvanometer for Microwaves

Furthermore, the frequency was a logarithmic function of the light intensity. In an attempt to duplicate this behavior, the circuit shown in Fig. 12 was used. The analogue-to-digital converter is represented by the circuit between the terminals ABCD. The eye cell is represented by the vacuum phototube. Although the output frequency was a linear function instead of a logarithmic function of light intensity; it was surprisingly sensitive. With 50 ft-candles of illumination the output frequency was 200 pulses/sec, but with the cell in a dark box the frequency went down to 10 pulses/hour. Although no extensive data were obtained, the output frequency range was near 6 decades. Replacing the photocell with a photomultiplier greatly improved the sensitivity at the ultimate point where the

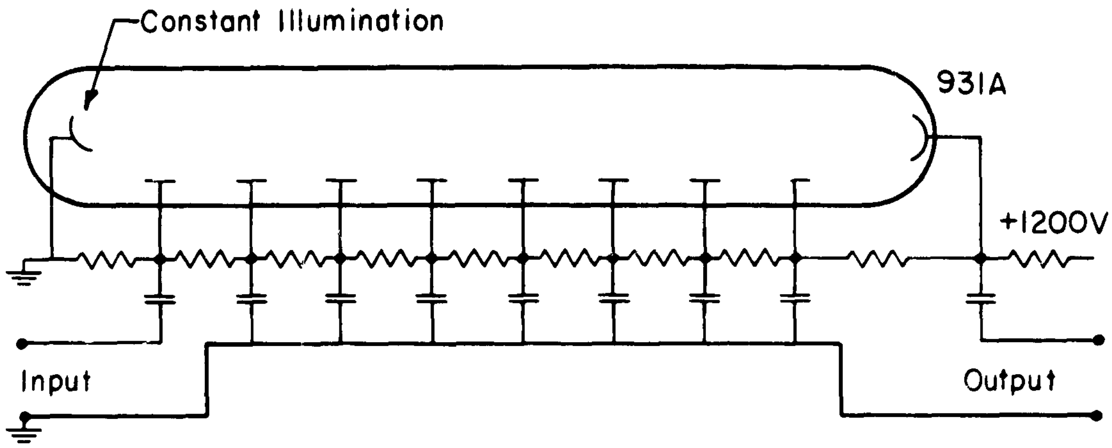

Fig. 11. Video Amplifier Using Secondary Emission Multiplier

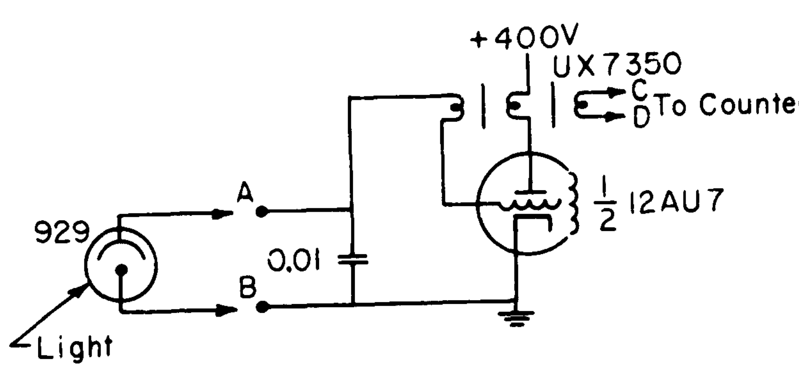

Fig. 12. Experimental Analog of Single Eye Cell

detector could still sense light, but the observer had difficulty in seeing the equipment. As the ultimate sensitivity is limited by the photocathode quantum efficiency further work on this device is unwarranted. Although this device failed to provide the logarithmic function, it does demonstrate a simple type of photon integrator which could also detect other forms of radiation by the use of a different transducer.

2. Microwave "Ear"

This scheme, shown in Fig. 13, is based on studies of the hearing mechanism in animals. It is of interest because it allows the simultaneous detection of signals over a broad band of frequencies (i.e., 200% bandwidth as opposed to <10% for commercial spectrum

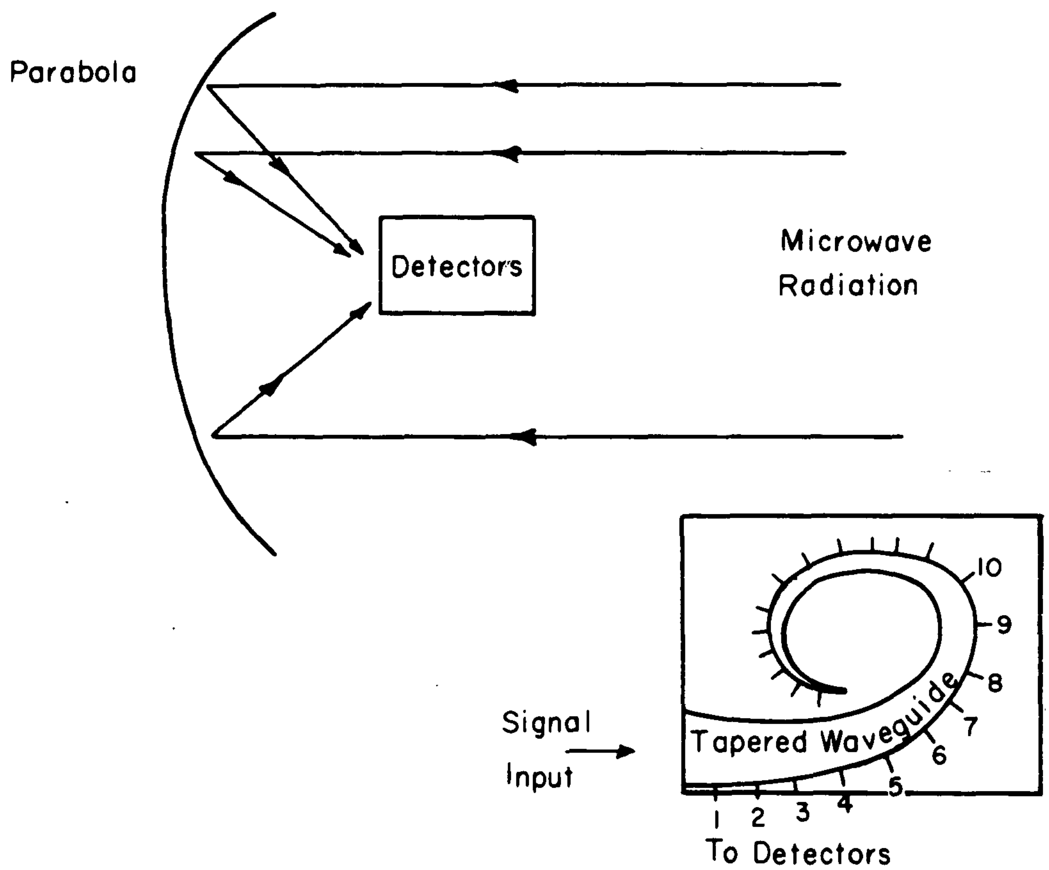

Fig. 13. Microwave Spectroscope

analyzers), and because the output is not channeled through the eyes or ears of the observer, but through his skin. In operation, signals propagating in the TE_{10} mode enter the tapered waveguide and travel along it until they reach cutoff. At this point the energy density for this frequency is a maximum. By placing a large number of sensitive detectors (such as superregeneration detectors using Esaki diodes along the guide and terminating their outputs on the skin of the observer, the observer could be made sensitive to microwave radiation. For reconnaissance purposesthis would mean that he would be able to detect and locate radars with a minimum amount of equipment. Furthermore the power requirements would be quite small since the nerves in the skin can detect relatively feeble currents. Through coupling to the skin, the observer is relieved of watching or listening to an artificial indicator. Objections to such a scheme include: (a) the microwave structure is difficult to build and operate in a single mode; (b) a large number of detectors (100-10,000) would require a large number of connections to the skin so that even if the detectors could be constructed on the exterior of the microwave structure, the cable bundle to the observer might be cumbersome; (c) prolonged contact with the skin could cause irritations; and (d) an extensive learning period may be required.

F. Superregeneration

Superregeneration is presented here not so much for the value of a single system or circuit, but for its over-all merit as a detection process. The superregeneration principle was first described by Armstrong in 1922[23] as a method of periodically switching a negative resistance into a tuned circuit so that oscillations will grow exponentially with time from the initial signal amplitude. It is interesting, for surveillance purposes, because of its ability to detect weak signals down to the level of the input circuit noise. This circuit noise may now be reduced because of resent developments in masers, parametric amplifier and tunnel diodes.[25,26,27] Detectors based on this principle are commonly simple devices with extremely high gains, but with poor selectivity, high noise figure, fluctuating gains, and re-radiation.[24] Since all of these effects except the re-radiation are attributable in some way to the net circuit resistance as a function of time, it should be possible to choose an idealized resistance function to minimize these objectionable features.

The fundamental relationship for superregenerative operation is shown in Eq. (2),

$$(2) \qquad E(t) = E_o e^{-\frac{Rt}{2L}} \sin \omega t$$

where t is time interval after negative resistance is switched in
R is equivalent circuit resistance $R < 0$ for $0 \leq t \leq t_1$
L is equivalent circuit inductance
E_o initial amplitude of oscillation at $t = 0$, t_3
ω angular frequency of resonant circuit
E amplitude of circuit oscillation.

The operational cycle is shown in Fig. 14. The cycle shown here differes from the one conventionally used for superregenerators in that a large value of resistance is used in the interval $t_1 < t < t_2$ to damp out oscillations rapidly instead of wasting part of the cycle times by allowing the normal losses to reduce the oscillations to the level of the incoming signal. During the sampling interval $t_2 < t < t_3$ the signal amplitude follows a transient growth depending on the signal amplitude and the circuit losses in the resonant circuit. During the amplification interval $0 < t < t_1$, the circuit resistance is made negative so that the oscillations grow from the initial level E_o for

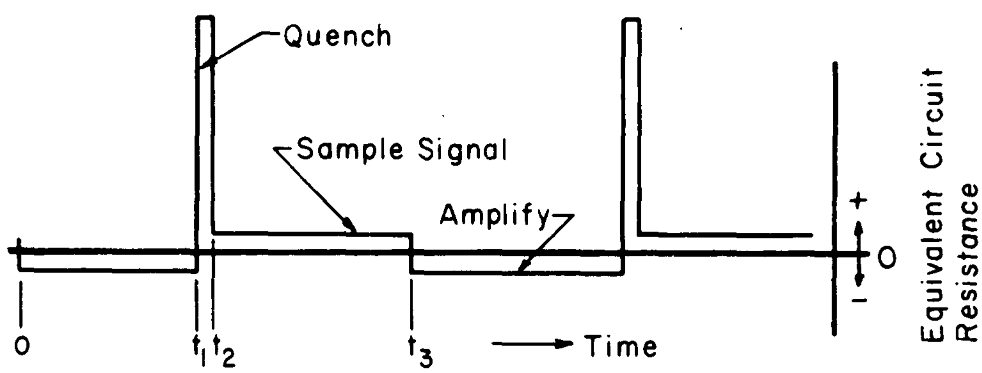

Fig. 14. Idealized Equivalent Circuit Resistance Cycle.

either a fixed time (linear mode), or until they reach a fixed amplitude E_m (logarithmic mode).

For operation in the linear mode the gain is the ratio of the final amplitude E_t to the initial amplitude E_o. To show this Eq. (2) is rewritten as[1] Eq. (3):

$$(3) \qquad A = E_{t_1}/E_o = e^{-\frac{Rt_1}{2L}}$$

Operation in this mode requires that the negative resistance be constant in order to provide constant gain. The variation in gain with small changes in the negative resistance is shown by differentiating Eq. (3):

$$(4) \qquad \frac{dA}{dR} = -\frac{(t_1 - t_o)}{2L} e^{-\frac{R(t_1 - t_o)}{2L}} = -\frac{\Delta T A}{2L}$$

and

$$(4a) \qquad \frac{\Delta A}{A} \approx \frac{\Delta T \Delta R}{2L}$$

This shows that the fluctuation in gain for fluctuation in negative resistance is proportional to the gain. Gains reported vary between 5 0 db and 80 db[25,39,41] so that the requirements on the stability of the negative resistance are correspondingly exacting. Perhaps one way around this is to use two or more synchorized superregenerators in cascade with reduced gain in each.

Operation in the logarithmic mode means that the time interval $t_1 - t_o$ is a function of the initial amplitude E_o. Solving Eq. (2) for this interval yields:

$$(5) \qquad t_1 - t_o = -\frac{2L}{R} \ln E_m/E_o .$$

The variation in time due to variation in R is obtained by differentiating Eq. (5):

$$(6) \qquad \frac{dt}{dR} = + \frac{2L}{R^2} \ln E_m/E_o$$

Where Eq. (5) and (6) are combined these results:

$$(7) \quad \frac{\Delta t}{t} \approx \frac{\frac{2L\Delta R}{R^2 \ln} \; {}^{E_m}/_{E_o}}{-\frac{2L}{R} \ln \; {}^{E_m}/_{E_s}} = -\frac{\Delta R}{R}$$

Which shows again that circuit stability depends on the negative resistance stability.

It should be pointed out that superregeneration can still be used in the degenerate case where the frequency is zero.The factor of 2 disappears from the exponent giving Eq. 8 (assuming a long sample period so that $R_o C << t_s$):

$$(8) \quad e_c = i_g R_o e^{-t/RC}$$

although this circuit, Fig. 15A appears indentical with the equivalent circuit for nerve tissue[4,5] with the (-R) and (c) formed by the nerve membrane, it has two features not found in biologic systems. These are: (1) output polarity depends on input polarity (unidirectional for nerve tissue), and (2) waveshape is exponential while nerve preparations commonly show sharp pulses. Fig. 15B shows the waveforms to be expected with this circuit. If i_g is the signal current and R describes the net circuit resistance vs. time then the peak amplitude of the capacitor voltage will be related to the initial amplitude by a constant as in eq.3.

G. Simplification For Pulsed Radars

It has been observed that the anode current in a c w magnetron is strongly dependent on the phase and amplitude of reflections occurring in its rf output system. For total reflection the variations were as high as 60% of the total current. Also Hill and Olsen[28] report that a smooth-anode coaxial magnetron, operated near 1200 mc, could be used to detect signals of -65 dbm to -70 dbm. Therefore it is suggested that the transmitting magnetron in a pulsed radar also be used at reduced power as the local oscillator-mixer combination with the I.F. frequency equal to the frequency shift in the oscillation frequency. This I.F. output would appear as fluctuations in the anode current in the magnetron during the receiving interval. Although this method might be objectionable because of local oscillator noise, it could eliminate the duplexer, crystal detector, and separate local oscillator. One additional advantage is that crystal burnout caused by high-level signals is avoided.

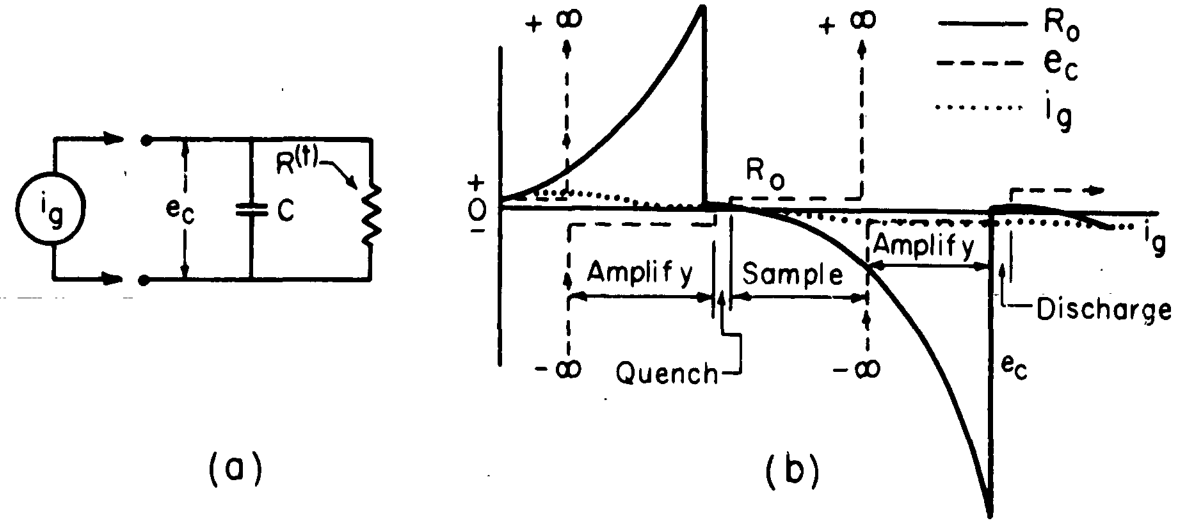

Fig. 15. D C Superregenerator.

V. Conclusions and Recommendations

The purpose of this study has been the investigation of new or unusual detection techniques for surveillance applications. As a consequence, a general survey of detection techniques, including biological techniques, and a study of existing detector sensitivities have been conducted during the past period. In this survey many interesting schemes have been proposed. Two of these, the detection of electromagnetic energy by an optical Faraday rotation shift and the detection of electromagnetic by piezoelectric effects are particularly interesting. For surveillance purposes an ideal electromagnetic detector would have near-unity quantum detection efficiency, be sharply selective to any desired frequency, be infinitesimal in size and require little maintenance or power. The microwave-optical detector appears to have the required sensitivity and wide tuning range, but is neither small nor simple. Its special interest is that it appears to be the forerunner of a new type of detector based on quantum-mechanical concepts. The piezoelectric detector can never approach unity quantum detection efficiencies or be easily tunable over wide frequency bands, but it is small, simple and requires little power. The successful development of these two devices would provide sensitive detectors in the millimicrowave region where such detectors are now lacking. This region is of primary importance for surveillance purposes since it contains much of the thermal radiation of man and his equipment. It also permits increased antenna directivity per given physical size. Also there is reason to believe that the application of these frequencies would alleviate the severe attenuation of signals transmitted from a hypersonic vehicle in an ionized atmosphere. Therefore it is on the basis of these considerations that we propose to continue the theoretical analysis and experimental investigation of these two detectors during the next contract period simultaneously with the continuing search for new and unique detection techniques.

Appendix VI. A Macroscopic Analysis of the Faraday-Rotation Microwave Detector by Dr. W.S.C. Chang

The Faraday effect (i.e., the rotation of the plane of polarization of light passing through a magnetic field) is very large, in general, in paramagnetic salts. It can be expressed as follows:

(9) $$\theta = A_1 \tanh \frac{\mu H_a}{kT} + B_1 H_a$$

where H_a is the effective applied magnetic field; T is the temperature of the spin system; μ is the magnetic moment; k is the Boltzmann's constant; and θ is the Faraday rotation angle in degrees per millimeter of path length.[43,44] Figure 16 shows a typical θ vs. H_a curve for $N_d (C_2 H_5 SO_4)_3 \, 6 H_2O$. Notice that this curve is normalized with respect to temperature; therefore it is applicable to $4.2^oK > T > 1.4^oK$. At these low temperatures ($4.2^oK > T > 1.4^oK$), only the Zeeman levels of the ground state are populated; therefore this "T" can be replaced by the spin temperature, T_s* of the paramagnetic levels. Moreover, when $\mu H_a << k T_s$,

(10) $$\frac{d\theta}{dT_s} \cong - A_1 \frac{\mu H_a}{k T_s^2}$$

or for $A_1 \tanh \frac{\mu H_a}{k T} >> B_1 H_a$

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* For an analysis of the spin temperature and the bath temperature, see Reference 45.

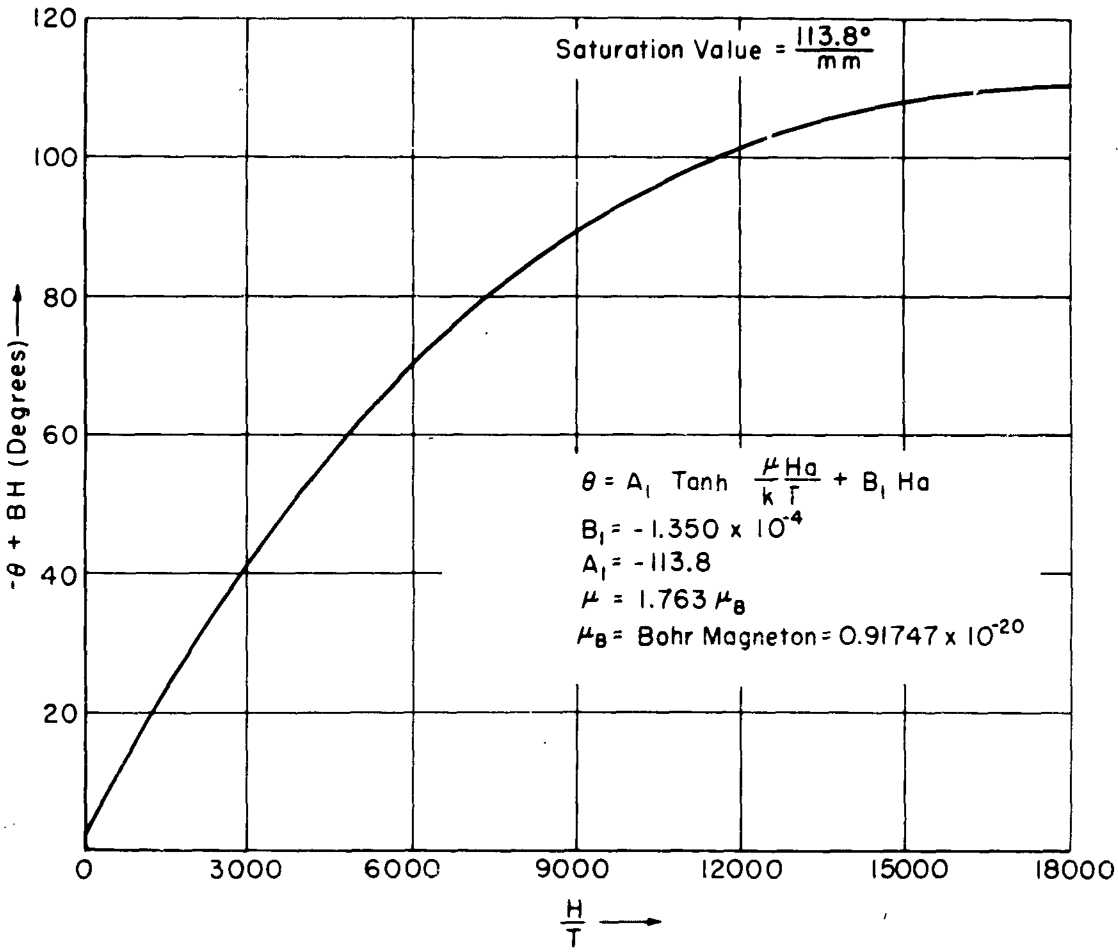

Fig. 16. Faraday Rotation in Single Crystals of $N_a(C_2H_5\text{-}S\ O_4)_3 6H_2O$

(11) $$\frac{\Delta \theta}{\theta_o} = - \frac{\Delta T_s}{T_s^o} .$$

These two conditions are usually satisfied for $T_s \cong 4^oK$ and $\mu H_a <$ 100 KMc. For $T_s > 4^oK$, Eq.(10) will always be $\cong$ and Eq. (11) should be modified to

(12) $$\frac{\Delta \theta}{\theta_o - B_1 H_a} = - \frac{\Delta T_s}{T_s^o}$$

Since T_s is the spin temperature representing the thermodymamic state of the spins, its value is not always equal to the value of the bath temperature when there is paramagnetic absorption.[45] As a matter of fact, T_s of a spin system is defined simply as the ratio of the populations of the pair of paramagnetic energy levels according to the Boltzmann distribution at the temperature T_s (i.e., $T_s \equiv \frac{E_2 - E_1}{k \log_e \frac{n_2}{n_1}}$, where E_2 and E_1 are the energy levels of the two spin states: n_2 and n_1 are the propulations of the E_2 and E_1 states). Where population inversion occurs such as in the masers, T_s would be negative. The saturation of paramagnetic resonance corresponds to $T_s = \infty$

On the other hand, the rate equations of[46] the population densities yield:

(13) $$\frac{dn_2}{dt} = n_1 w_{12} - n_2 w_{21} + (n_1 - n_2) \overline{w}$$

(14) $$\frac{dn_1}{dt} = n_2 w_{21} - n_1 w_{12} + (n_2 - n_1) \overline{w}$$

(15) $$w_{12} = w_{21} e^{-(E_2 - E_1)/kT_b}$$

where w_{12} is the relaxation rate from E_1 to E_2; T_b is the temperature of the liquid helium bath; $\overline{w}$ is the induced transition probability of the paramagnetic resonance; and under steady state conditions; $\frac{dn_2}{dt} = \frac{dn_1}{dt} = 0$. Therefore, for $\mu H_a << k T_b$ and $E_2 - E_1 = \mu H_a$,

(16) $$\frac{n_2 - n_1}{n_1} = \frac{\mu H_a}{k T_b} \frac{\frac{w_{12}}{\overline{w}}}{1 + \frac{w_{12}}{\overline{w}}} ,$$

or

(17) $$T_s = T_b \frac{\bar{w} + w_{12}}{w_{12}} .$$

But

(18) $$\bar{w} = \frac{P_{abs}}{(n_2 - n_1)\mu H_a} ;$$

therefore

(19) $$\frac{\Delta 0}{0_o} = - \frac{T_s - T_b}{T_b} = - \frac{P_{abs}}{w_{12}\ (n_2 - n_1)\ \mu\ H_a} .$$

From the microwave power absorption point of view, as long as the unloaded Q of the cavity is much greater than the magnetic absorption Q of the cavity, P_{abs} would be approximately equal to P_{in} (i.e., the total microwave power input) times the effect of coupling. Hence

(20) $$\frac{\Delta 0}{0_o} = - \frac{P_{in} \left(\frac{4\beta}{1+\beta}\right)^2}{w_{12}\ (n_2 - n_1)\ \mu\ H_a}$$

where β is the coupling coefficient, $\beta = \frac{Q cavity}{Q\ ext.}$.

In other words, the Faraday rotation effect would directly measure the power input for very low power levels where the saturation does not occur. Assuming that

$\mu H_a = 10$ KMC $= 6.624 \times 10^{-24}$ joules

$w_{12} = 200 \frac{1}{sec}$ (i.e., 5 milliseconds for the relaxation time)

$n_2 - n_1 = \frac{n_o}{2} \left(\frac{\mu Ha}{k\ T}\right) \cong 10^8$ at 4^o K for $n_o \cong 10^{19}$ spins

$\beta = 1$ for the critically coupled cavities,

then

(21) $$\Delta 0 = \frac{P_{in}\ (watts)}{6.624 \times 10^{-3}} \times 0_o .$$

If the sample is 5 millimeter to 1 cm thick and the sensitivity of detection is 3^o_g corresponding to a $\frac{\Delta 0}{0_o} \cong \frac{1}{2}$ % for a very crude optical measurement of Δ O, then the minimum detectable $P_{in} \cong 6\ \mu$ watts.

Comparing this value with the data obtained by J. M. Daniels and his colleagues in the University of British Columbia where they have obtained saturation of the paramagnetic resonance with 40 μ watts of power, it is concluded that the power measuring sensitivity of an ordinary crude Faraday detection system would be in the order of magnitude of 10^{-6} watts.

In order to improve this sensitivity it is obvious that a paramagnetic crystal must be sought for which the coefficient A' is large and a detection system must be used for which the minimum detectable $\Delta 0$ is small. The coefficient A' for various crystals can be measured simply by observing the Faraday effects of the H_a without paramagnetic resonance. The minimum detectable angle $\Delta 0$ can be decreased if a Fabry-Perot interferometer is constructed by using two partially reflecting surfaces perpendicular to the optical axis at both ends of the crystal. The effect of such an interferometer can be estimated by geometric optics as follows. Let the original incident light be polarized along the x' direction and the optical axis of the paramagnetic material be along the z direction as shown in Fig. 17. Then, if the angle of rotation through the crystal is 0 for each path and the reflection coefficient for the electric field is Γ, following relationships for the emergent light at B are obtained:

(22) $$E_{By'} = E_o T^2 \left[\sin 0 + \sin 30\, \Gamma^2 + \sin 50 \cdot \Gamma^4 + \ldots\ldots\right]$$

(23) $$E_{Bx'} = E_o T^2 \left[\cos 0 + \cos 30\, \Gamma^2 + \cos 50 \cdot \Gamma^4 + \ldots\ldots\right]$$

(24) $$E_B = E_{By'} \underline{iy'} + E_{Bx'} \underline{ix'}$$

Where T is the transmission coefficient of the electric field and E_o is the incident electric field.

If a proper x and y axis are chosen in such a way that

(25) $$\underline{ix} = \cos\psi\, \underline{ix'} + \sin + \psi\, \underline{iy'},$$

(26)
(27) $$\underline{iy} = -\sin\psi\, \underline{ix'} + \cos\psi\, \underline{iy'}$$

where $\tan\psi = \dfrac{E_{By'}}{E_{Bx'}}$,

then it follows that

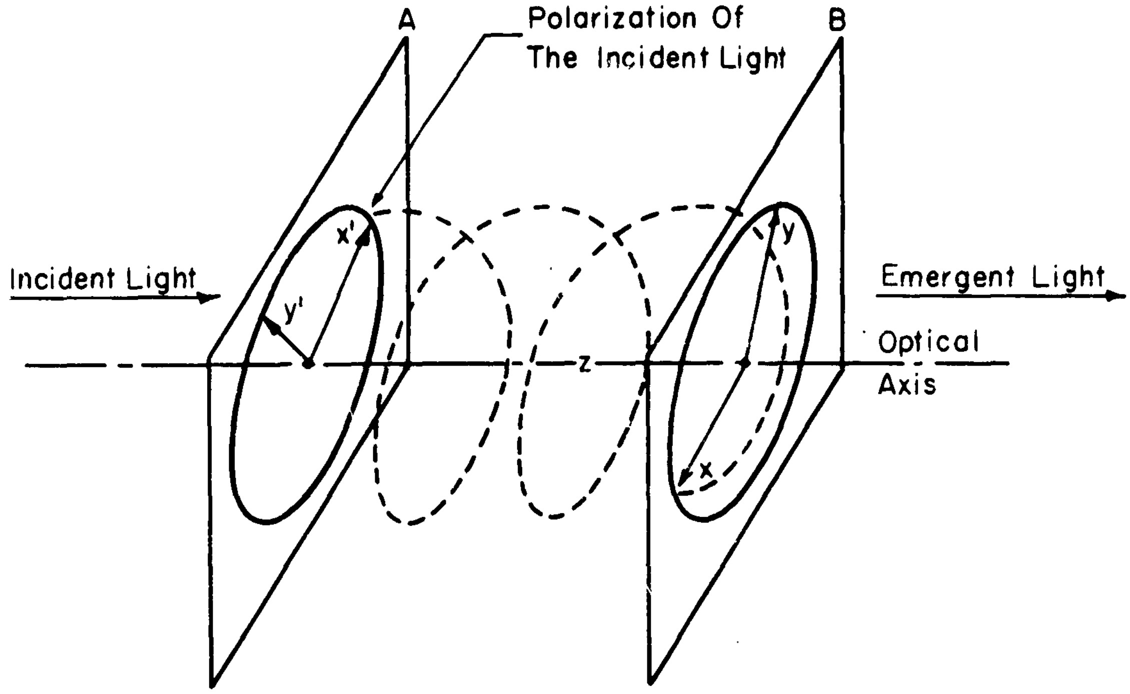

Fig. 17. The Proposed Fabry-Perot Interferometer.

(28) $$E_{BX} = E_{BX^1}\cos\psi + E_{By^1}\sin\psi = \sqrt{E_{BX^1}^2 + E_{By^1}^2}$$

(29) $$E_{By} = E_{By^1}\cos\psi - E_{BX^1}\psi = 0$$

Therefore, if an ideal polarizer is placed after B along the iy direction, there would not be any light transmitted through this polarizer. When a small change in 0, $\Delta 0$, is caused by the paramagnetic absorption,

(30) $$E_{By} \cong E_o T^2 \Delta 0 \left[\cos(0_o-\psi) + 3\cos(30_o-\psi)\Gamma^2 + 5\cos(50_o-\psi)\Gamma^4 + \ldots\ldots\right]$$

$$\cong E_o T^2 \Delta 0 F$$

where, for an interferometer of length ℓ_{AB},

$$(31) \qquad 0_o = \left(A_1 \frac{\mu H_a}{kT_b} + B_1 H_a \right) \ell_{AB}.$$

Thus, the effect of the Fabry-Perot interferometer is to increase the effective path length of the Faraday rotation by a factor of

$$(32) \qquad F = \cos(0_o - 4) + 3\cos(3\,0_o - 4)\,\Gamma^2 + 5\cos(5\,0_o - 4)\,\Gamma^4 + \ldots.$$

To estimate the magnitude of F, let it be assumed that

$$(33) \qquad 0_o = n\pi \quad (n = 0, 1, 2, 3, ----); \text{ then}$$

$$F = \cos(0_o - \psi)\left[1 + 3\Gamma^2 + 5\Gamma^4 + \ldots\ldots..\right]$$

$$= \cos(n\pi - 4)\left[\frac{2}{(1-\Gamma^2)^2} - \frac{1}{1-\Gamma^2}\right].$$

For $\Gamma = 97.5\,\%$, $F = 1{,}000 \cos(n\pi - \Psi)$;
For $\Gamma = 99.1\%$, $F = 10{,}000 \cos(n\pi - \Psi)$.

Therefore, the effect of the Fabry-Perot interferometer alone could reduce the minimum measurable $\Delta 0$ by three orders of magnitude and increase the sensitivity of the Faraday rotation detector to 10^{-9} or 10^{-10} watt.

On the other hand, the size of the crystal can be decreased by changing its transverse dimension alone without affecting the longitudinal dimension or the effective path length of the optical light. The crystals can also be diluted with diamagnetic ions to increase the spin-lattice relaxation times. When these changes are taken into account in Eq. 20, their total effect would improve the sensitivity of the detector by two or three more orders of magnitude. Therefore, it may be concluded that the sensitivity of such a device would be expected to be about 10^{-10} to 10^{-13} watts depending upon the properties of the materials as well as the refinements of the measuring techniques.

Such an electromagnetic detector has never been demonstrated before. It provides one method where the electromagnetic radiation is detected by means of the atomic interactions. The ultimate sensitivity of such a device is limited by the control of the environments such as both temperature and H_{dc}, the sensitivity of the optical detectors, and the quantum limits of all the atomic detectors that have been proposed.[47,48] It may be said that one of the fundamental limits on the atomic detectors is the minimum number of changes of spins for change of T_s that are detectable. The investigation of the present detector will lead to some understanding of this limitation which may lead us to much more sensitive detectors. Moreover, as in all atomic detectors, this interaction can take place equally well at milli-microwave frequencies using the Stark effect energy levels and interferometers. Therefore, this principle has the potential of leading to the development of very sensitive millimicrowave detectors.

The present analysis is presented on a macroscopic approach to gain some physical insight into this detector. A quantum statistical analysis of the interactions of the Faraday effect and paramagnetic resonance has been made by Rosenfeld[49] and Opechowsky.[50] This detailed microscopic analysis will be presented in a future report. One interesting result of the exact theoretical analysis is that the Faraday rotation is dependent not only on the T_s, but also, through a cross modulation process upon the magnitude of the rf field. If this effect can be made predominant, one can use it either as an optical modulator or as a detector which has a time response many orders of magnitude faster than that of the Golay detector.

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