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Research on Submillimeter Wave Generation and Techniques

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1. Introduction

The search for means to operate radio-frequency generators at ever higher frequencies has traditionally been a most challenging and important endeavor. Advances in generation methods have expanded the technically useful frequency spectrum and made possible new and diversified applications.

Recently the gains made in the microwave region have been solidly consolidated, and work in the millimeter region has been given more emphasis. The new frontier is the submillimeter region extending from one millimeter down to one tenth of a millimeter, and therefore, in a sense, linking the radio spectrum to the far infrared optical region. Up to now the lack of sources with useful power output has virtually prevented the exploration of the submillimeter range, and comparatively little is known about the physical properties of submillimeter wave radiation. There are substantial gaps in our knowledge of the propagation of these very short waves in the atmosphere. On the other hand guided transmission for communication purposes appears very promising in view of certain basic considerations, but the potentialities must still be evaluated in details. Thus it is somewhat futile to engage in prophesies concerning the future usefulness of the submillimeter range for specific applications.

However, the quasi-optical aspects of submillimeter wave radiation is sure to become a most valuable asset for many applications. An extremely narrow beam with angular width of 4 minutes can be produced at a wave length of 0.5 mm and with an antenna dish diameter of 1 m. The near field of this antenna would extend all the way out to 2 km. The available bandwidths are impressive. At a wave length of 0,1 mm a channel with 1% relative bandwidth contains a frequency spectrum equal to that between d-c and the high frequency limit of the microwave region. Very narrow percentage bandwidth components can thus be expected to have tremendous channel capacities. Finally, in the realm of scientific instrumentation, the outstanding value of millimeter and submillimeter wave radiation as a tool to probe into the structure of matter hardly needs particular mention.

A breakthrough in the generation of coherent submillimeter radiation is urgently needed; once this has been achieved one can with confidence expect the fruition of an exciting new field of scientific and technical activity.

At the General Telephone & Electronics (GT&E) Laboratories, a long-range basic research program on submillimeter wave generation and related problems was started several years ago as an extension of work on backward-wave oscillators for the millimeter region. This paper deescribes some aspects of currents research in this field at the GT & E Laboratories.

2. The Problem of Submillimeter Wave Generation

During the past decade microwave generation techniques have been successfully extended into the millimeter wave range, and it is tempting to anticipate that these methods might be extended to still shorter wave lengths. However, because of current-density and focusing requirements, the scaling down of conventional microwave tubes soon becomes impracticable. In addition, the power-handling capabilities of fragile interaction structures decreases rapidly and severely limits the beam d-c input power, while at the same time increasing r-f losses push start-oscillation currents far beyond present technical possibilities.

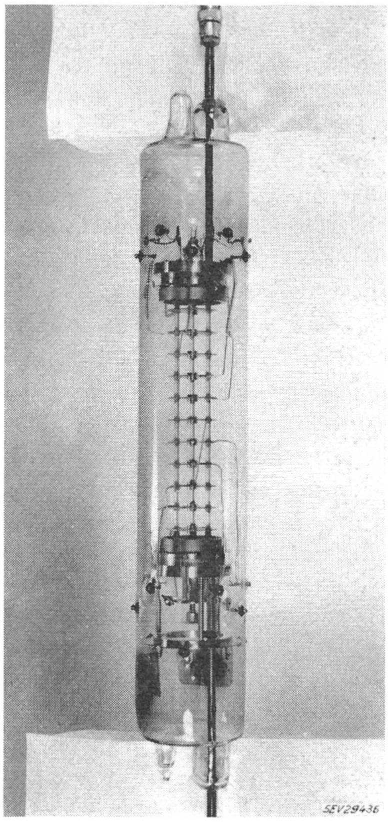

Fig. 1

Experimental ripple velocity tube with *S*-band cavity couplers

This situation could be somewhat eased if one had a mechanism by which the r-f modulation of the electron beam could be enhanced without the necessity of employing interaction structures tightly coupled to the beam. For such a mechanism to be useful, it would be sufficient to have input and output couplers with relatively low efficiency of energy transfer, but designed to handle adequate d-c beam power. Such a tube would depend on a "circuitless" middle section to produce an overall gain sufficient to permit the start of oscillations. Along this line of thought it has been proposed to shoot a beam of electrons though a plasma to achieve amplification with no metallic interaction structure.

In a plasma column [1][1]), under certain conditions, there are indeed modes of wave propagation suitable for interaction with electron beams. If a backward wave mode is chosen, one already has a suitable internal feedback path built into the system. However, as one goes to higher frequencies the problem of generating, maintaining and confining a sufficiently dense plasma becomes very difficult to solve. Even if solutions to these problems became available, the output coupler would, of course, finally determine the highest frequency at which still useful amounts of power could be extracted.

In this connection it may be interesting to recall that there are simple methods available to build up the r-f modulation on a beam without a plasma or a metallic interaction structure. The so-called velocity jump amplifier is an example. Some years ago an experimental tube was built in the GT&E Laboratories in which the beam was made to drift through a series of ring electrodes alternately connected to lower and higher d-c potential and spaced one eighth of the beam plasma wave length apart. This device was called a "ripple velocity tube" because of the periodic acceleration and deceleration to which the beam is subjected. A photograph of the tube is shown in Fig. 1. The cavity couplers were designed to operate in the *S*-band. The diameter of the ring apertures is many times larger than that of the beam. The ripple velocity structure enhances the beam modulation over a wide frequency range, since the proper spacing of the aperture does not depend on the signal frequency. By switching the ripple potential on and off the output power level was observed to change up to about 20 db. Our results indicated that, with the development of suitable couplers, the operation of this type of tube might be extended to cover a major portion of the millimeter region.

Several schemes for the generation of submillimeter waves have, over a rather long period of time, been proposed. Among these might be mentioned the so-called Undulator [2] in which bunched electrons at relativistic velocity are made to radiate through «Bremsstrahlung» by causing them to move along a sinusoidal path forced upon the electrons through the action of a suitably designed transverse magnetic field. In this scheme the energy is coupled out of the beam without the usual circuit limitations. On the other hand, one realizes that, unless the desired frequency component is already contained in the current modulation of the beam, radiation will be emitted randomly and of an intensity corresponding to the shot noise in the beam. The linear accelerator employed to accelerate electrons to relativistic velocities actually produces nonlinear bunching and therefore straightforward frequency multiplication, on which the emitted submillimeter wave radiation depends entirely.

Another relativistic device, the Harmodotron [2], again utilizes frequency multiplication by tight electron bunching for the generation of millimeter waves, but uses cavity-type beam couplers instead of «Bremsstrahlung»-effects. The relativistic velocity of the beam electrons makes it possible to couple to fast circuit waves. Due to this feature the coupler can be built much larger and with higher d-c power-handling capabilities than would be possible with non-relativistic beams.

[1]) Refer to the Bibliography at the end of the article.

Experimental work in a number of university laboratories has shown that, in principle, operation according to the approaches described is possible. Further development of these devices, however, has turned out to be difficult, and, in some cases, the ultimate performance limitations are not clearly understood.

This situation motivated GT&E to continue searching for other approaches. Work has since led to the concept of a new class of electron devices to employ recent advances in the art of producing ultra-high magnetic fields [3; 4; 5].

3. An Approach Using Pulsed, Ultra-High Magnetic Fields

The achievement of high power coherent submillimeter wave radiation with an electron device requires the solution of certain fundamental problems; the principal ones will be mentioned. A large number of electrons must be contained in a volume small compared with a wave length in its transverse dimensions; they must carry sufficiently high energy; and they must be subjected to substantial acceleration in order to couple power out by direct radiation.

The use of ultra-high magnetic fields can help to provide the solution to all three of the problems cited. Electrons can be maintained at the Brillouin charge density by the field, they can be made to orbit at cyclotron frequency in an orbit smaller than a wave length with rotational kinetic energy approaching the rest energy of the electron, and in the submillimeter range the centripetal acceleration is sufficient to produce substantial power in the radiation field. The key to achieving coherence is recognition of the fact that the electrons must orbit about a common axis parallel to the magnetic field and in any plane perpendicular to the magnetic field they must be confined in a bunch which subtends a small angle at the axis i. e. they must be focused in phase.

A device based on these principles must incorporate a mechanism for preparing the final radiating state of the electrons, either continuously or intermittently. A particular embodiment of these principles has been devised and is being investigated in detail, both theoretically and experimentally [6]. In this embodiment, called the Tornadotron[2]), the radiating state is prepared sequentially so that the emission of radiation is inherently intermittent. Basically, the Tornadotron performs energy conversion from microwave to submillimeter wave lengths in a cycle of operations consisting of four phases: First, electrons are injected and trapped inside a chamber. Then orbital motion of the electron cloud is induced through the use of cyclotron resonance at a microwave frequency. In the next phase the frequency of the orbital motion, and the rotational kinetic energy associated with it, is increased by a factor of a hundred to a thousand by applying a pulsed high magnetic field. Radiation of submillimeter wave power is then obtained directly from the rapidly swirling electron cloud.

The experimental work thus far on the Tornadotron has demonstrated the trapping of electrons and their prolonged confinement inside a small chamber to be entirely practical,

[2]) The name of the device refers to one of the characteristics of operation, involving a swirling motion of trapped electrons rotating about an axis while at the same time describing a circular orbit in space, very much like a moving vortex.

and much has been learned about these mechanisms. Cyclotron excitation of the space charge cloud has also been studied, and free "ringing" due to orbital motion of the cloud was observed after the exciting microwave pulse had been shut off. At this time equipment is being designed and built to pulse the orbiting electron cloud with magnetic fields of the order of 100 kGs[3]). Another magnetic pulser is in the planning stage; it will reach peak fields well above 600 kGs. With such a field radiation at 0.18 mm is anticipated.

In the following pages a summary of the most important aspect of this work is given.

Trapping Phase

The operation of the Tornadotron depends on the trapping and prolonged confinement of an electron cloud in a chamber. In conventional electron devices, free electrons remain in the device for a typical transit time of 1 ns[4]), whereas in the Tornadotron a relatively large number of electrons must be trapped and confined for tens of microseconds in order that they may be operated on sequentially. The accumulation and trapping of electrons is accomplished by injecting them into a cylindrical chamber and applying time-varying voltages to the electrodes that bound the chamber. Subsequently, the axial confinement of the electron cloud is accomplished by means of static electric fields and the radial confinement by means of a uniform magnetic field directed parallel to the axis. Once confined, an electron would require the addition of several hundred electron volts in order for it to escape to one of the bounding electrodes. As a consequence, much more prolonged confinement is possible in this configuration than, for example, in a magnetron where escape is energetically possible but where electrons may undergo many transits.

Those aspects of the electrode configuration of the Tornadotron relevant to the trapping phase are shown schematically in Fig. 2, together with the axial potential distribution. A double-stream electron beam which penetrates the trapping chamber is established initially. At some instant the positive voltage applied to the ring electrode begins to increase linearly, and during this period, the parabolic potential well at the axis of the trapping chamber becomes progressively steeper. An electron that passes the retarding field with thermal velocity is first accelerated toward the repeller, decelerated and reflected, and then accelerated back toward the gate electrode. However, the electron is then not able to penetrate the potential barrier in front of the gate electrode because it has meanwhile become deeper. Thereafter, the electron continues to oscillate parallel to the axis of the chamber, and while its kinetic energy increases due to the time-dependent field in the chamber, it does not increase at a rate sufficient to overcome the decreasing potential energy. Thus during the period when the ring voltage is rising, there is a net flow of electrons into the chamber and a continuous accumulation of trapped charge. When the ring voltage reaches its terminal value, the gate voltage is pulsed negative, effectively "pinching off" the electron beam from the trapped charge cloud. The increase in depth of the potential well due to the increasing ring voltage is partially offset by the local space-charge fields, and this then presents a limiting mechanism for the amount of charge which can be trapped.

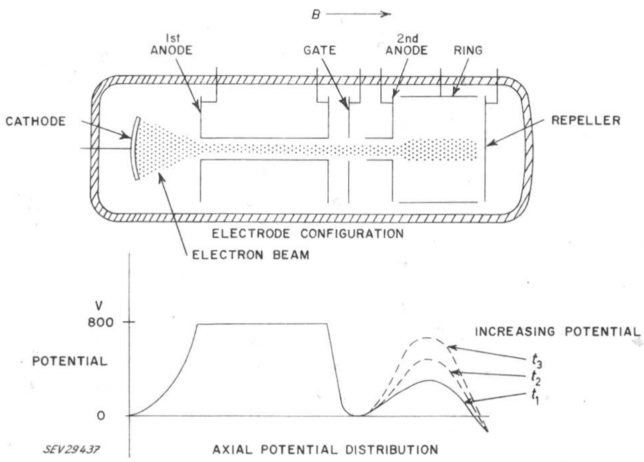

Fig. 2

Schematic representation of electron Trapping tube

Above: Simplified cross-section through trapping tube

B indicates the longitudinal magnetic field. The flux density at the first anode is 300 Gs, increases to 1000 Gs, at the gate and is homogeneous between the second anode and the repeller. The electron gun is magnetically shielded

Below: Axial potential distribution along the axis

In an experimental tube, built especially for the purpose of studying the trapping mechanism, the electron beam is launched by a converging Pierce gun and enters a 300-Gs magnetic field at its minimum focus. It then passes through a 4½ inch (110 mm) drift tube at 800 V along which the magnetic field is increased adiabatically to 1000 Gs, resulting in a compression of the beam. The retarding field arrangement consists of two 0.008-inch (0.2 mm) diameter apertures separated 0.030 inch (0.75 mm). Those electrons which pass through the potential minimum in front of the second aperture or gate electrode then enter a cylindrical trapping chamber 0.5 inch (12.5 mm) long and 0.5 inch (12.5 mm) in diameter bounded by the second anode, the ring electrode and the repeller. The second anode is maintained at 25 V positive with respect to cathode, but electrons are prevented from striking it by the magnetic field. The repeller is maintained at 20 V negative. The ring electrode is initially at 300 V and is increased to 1000 V in 14 μs during the trapping period.

With this tube it was possible to trap space-charge clouds of up to 7×10^8 electrons and keep this charge in the chamber for intervals far in excess of 1 ms. The cloud occupies a cigar-shaped volume 0.5 inch (12.5 mm) long and 0.050 inch (1.25 mm) average diameter.

In order to measure the trapped charge and geometry of the confined cloud, it was necessary to devise a new diagnostic technique. A particularly sensitive, non-destructive method was adopted which consists in measuring the change of impedance due to the electron cloud at the end electrodes of the trapping chamber (second anode and repeller). Motion of the electron cloud is induced by application of a UHF signal to the end electrodes and the resulting

[3]) kGs = kilogauss.

[4]) 1 ns (nanosecond) = 10^{-9} s.

induced currents are detected. At very low frequencies the displacement of the cloud is directly proportional to the applied force and the cloud appears to increase the capacitance between the end electrodes. At very high frequencies the "inertial force" predominates, the displacement is 180° out of phase with the applied force, and the cloud appears as an inductance. At any frequency the impedance of the cloud can be represented by a series resonant circuit. This circuit is shunted by the stray capacitance between the end electrodes and the combined circuit exhibits both a series and a paralle resonant frequency.

The trapped charge can be determined uniquely from the series and parallel resonant frequencies, the stray capacity and the dimensions of the chamber. Further refinements of the method enable one to extract information on the effective diameter of the cloud and to cross-check the measurement of trapped charge by an independent determination.

Additional insight into the process of electron trapping can be obtained by measuring the distribution of electrons with respect to binding energy. This measurement is made by placing equal and opposite adiabatic pulses on the end electrodes. The charge cloud is temporarily displaced, and those electrons with binding energies less than the pulse amplitude are collected. The charge remaining in the chamber is then measured, and by varying the pulse amplitude a complete energy distribution can be obtained. Fig. 3 is a photograph of the trapping tube with solenoid and auxiliary pulsing circuity and power supplies.

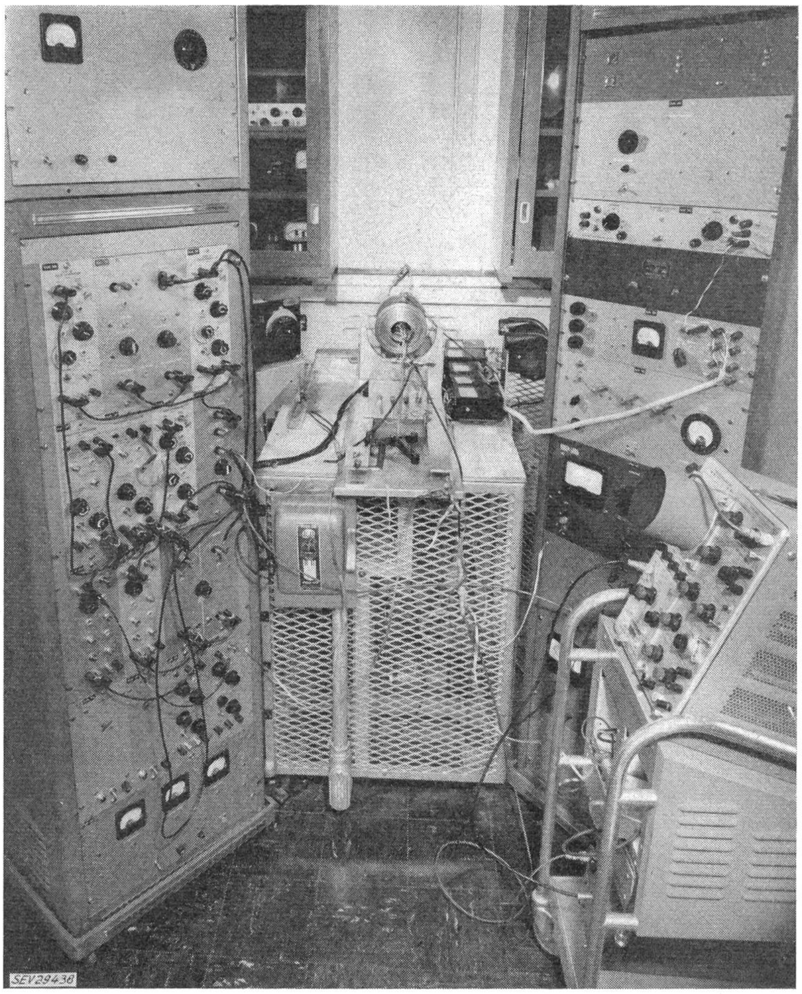

Fig. 3
Overall view of Equipment for Trapping Experiment
Electron Trapping tube and auxiliary electronic equipment

Pumping Experiment

Another experimental tube has been constructed which is basically similar to the tube used in the trapping experiment, but which incorporates modifications of the trapping chamber that are relevant to the pumping phase, as illustrated by Fig. 4. The basic objectives of the experiment are to verify the mechanism by which rotational kinetic energy is imparted to the cloud, and to demonstrate the persistence of phase ordering in the orbiting cloud in the absence of an impressed signal, which is of fundamental importance in the radiation phase. The trapping and confinement of the charge cloud are accomplished by the method described previously in connection with the trapping phase experiment. After trapping is completed a transverse r-f field at cyclotron frequency is pulsed on for a few microseconds by driving the segments of the ring electrode, and the cloud spirals out from the axis to an orbit whose radius is determined by the amplitude and duration of the applied r-f field. After the field is removed, the cloud continues to orbit for a time and induces r-f currents in the ring segments. There are two competing processes which conspire to cause a decay in the induced current after the r-f field is removed. Relaxation of the orbital excitation may occur as a result of resistive loading in the external circuit, which causes the cloud to spiral in toward the axis and give up its rotational kinetic energy, or phase disordering may sharply reduce the net induced current, in which case the rotational kinetic energy is main-

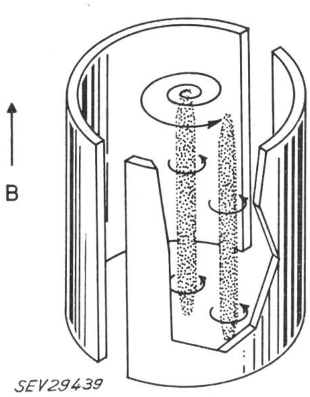

Fig. 4
Schematic representation of trapping chamber with orbiting electron cloud during pump phase
The end plates of the chamber are left out for clarity. The pumping field is applied between the two segments of the ring electrode
B indicates the homogeneous axial magnetic field

tained but in a relatively inaccessible state. The external circuit is designed in such a way that a low reactance is presented to the ring segments when the r-f field is removed. Provision is also made to introduce controlled inhomogeneities into the magnetic field in order to study the effect of phase disordering. In addition, the impedance presented to the ring segments can be used to obtain an independent measurement of trapped charge, which is analogous to that obtained from the impedance presented to the end electrodes. The orbiting charge cloud again behaves as a series resonant circuit, but in this case the series resonant frequency is the cyclotron frequency.

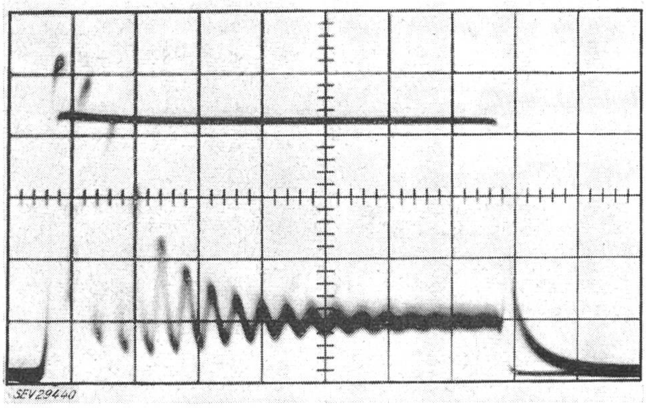

Fig. 5
Scope trace of pumping phase
Transient and free ringing

Fig. 5 shows an oscilloscope trace representing the instantaneous amplitude of microwave current in the leads of the split-ring electrodes during pumping. The time scale is 2.5 μs per division. Without trapped space charge only the square wave pulse of the klystron output is seen. With trapped space charge, however, a strong transient is observed when the microwave field starts displacing the cloud from its position on the axis. The transient dies out when the cloud is orbiting with a steady-state radius, which is determined by the generator impedance as seen from the cloud. Note the spike occurring when the free ringing of the cloud sets in; this happens because the currents as induced by the orbiting charge are no longer partially cancelled by the current impressed by the pumping generator.

From the analysis of the experimental data it becomes clear that the time constant of free ringing is not yet determined by phase disordering of the cloud, but rather by the loading of the cloud due to a resistive component of external circuit impedance appearing across the plates. With the present tube, free ringing times of up to 8 μs have been observed. The loading effect cannot be substantially reduced with the present tube, but ways were found to eliminate this kind of loading in future tubes, and substantially longer ringing times can be expected.

In conclusion, it can then be said that the work described here has given valuable insight into the behavior of trapped electrons under static and orbiting conditions. Results obtained so far have been most encouraging. The next phase of experimental work will be concerned with magnetic pulsing and will make it possible to evaluate the device capabilities of the Tornadotron in a more precise manner.

It should be emphasized that the Tornadotron is only one particular embodiment of devices utilizing ultra-high magnetic field and making use of a new method to trap and confine electrons in a controlled manner. The specific goal of the present work is the attainment of high-power pulsed submillimeter wave radiation, but in the long run other devices such as continuous-wave sources will make use of the new techniques being investigated.

4. Work on Instrumentation

Because of the extremely short wavelength involved, it will not be feasible to employ conventional microwave circuitry for the transmission and detection of submillimeter-wave power radiated by the Tornadotron.

Submillimeter-wave optics is defined essentially by the limitations and requirements imposed on optical components in the submillimeter range. In conventional light optics the basic components are glass lenses and prisms whose operation can be analyzed in terms of geometric optics. Diffraction effects determine the limit of resolution of highly corrected lenses and form the basis for some specialized components such as diffraction gratings, but can safely be neglected in most applications. In the submillimeter range glass is too opaque for use in lenses and prisms and most of these components become dimensionally impractical in the submillimeter range. Diffraction limitations are dominant in this wavelength range.

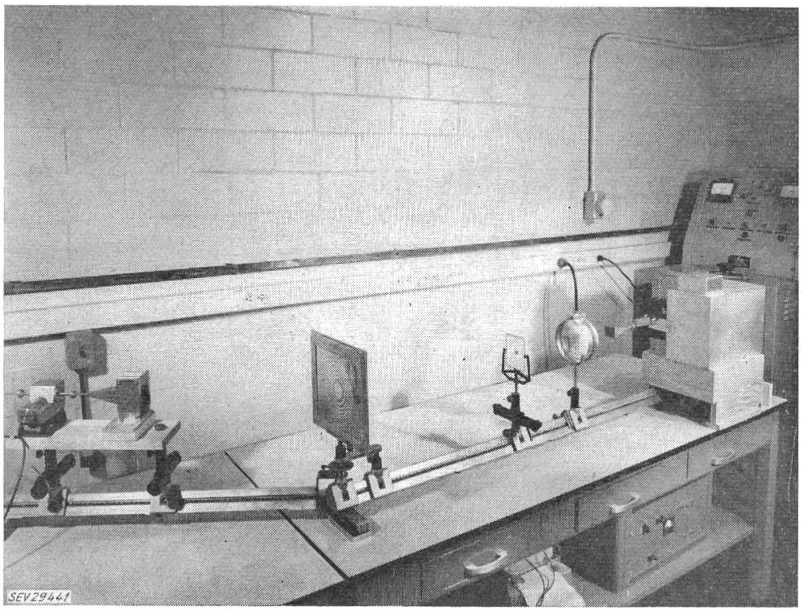

Fig. 6
Optical bench with Germanium wafer sample

Several components are already being investigated for use in the millimeter range which are suitable for scaling to the submillimeter range. Fresnel-zone lenses and diffraction gratings were fabricated by a photoresist etching process on milar film 0.002 inch (0.05 mm) thick which is coated with a few microns of aluminium, and evaluated at a wavelength of 4 mm. A polarizing filter for the same wavelength was constructed by stacking a series of thin conducting plates separated by 1/16 inch (1.6 mm) dielectric layers. This component also acts as a high-pass filter in the orientation in which the 4-mm waves are blocked and the third harmonic passes with negligible attenuation.

The printed Fresnel lenses and gratings have the virtue that their performance can be predicted throughout the submillimeter range where the attenuation and index of refraction of the dielectric materials is not yet known.

In Fig. 6 an optical test bench set-up is shown which is used to test components for the millimeter and submillimeter range. The particular experiment shown is part of a basic investigation of the nonlinear effects in bulk semiconductor material being conducted as an interdepartmental project at the GT&E Laboratories. If high electric fields are impressed on the semiconductor, in this case an n-type wafer of single crystal germanium 1 mil (0.001 inch = 0.025 mm) in thickness, the current density bears a nonlinear relation to the electric field. The effect arises because the mobility of carriers decreases with an increase in average energy [7]. To avoid heating of the sample, duty cycles of only 0.003 or smaller are used.

In this experiment a plastic lens concentrates the full output of a pulsed magnetron onto the germanium sample. Changes in d. c. conductivity are monitored and radiation from the backside of the crystal plate is analysed for harmonic output content.

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Plasma Containment and Radio-Frequency Fields

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537.525.1 : 537.533.3

1. Introduction

The problem of plasma containment is a crucial one in controlled fusion research. For the generation of interesting amounts of controlled fusion power, plasma densities above 10^{14} ions/cm^3 and plasma temperatures above 10^4 eV ($\approx 10^8$ °K) are required. The corresponding pressure of the plasma to be contained then is of the order of several atmospheres, in most cases above 10 atmospheres. Containment times of the order of a second are required [1,2][1])[2]).

Most of the work on plasma containment so far has been concerned with the use of d-c magnetic fields, or pulsed magnetic fields behaving, from the standpoint of plasma containment, essentially like d-c magnetic fields. The reason for this is the following. The average pressure p exerted by electro-magnetic fields on a plasma is limited by the relation:

$$p \leqq 0{,}5\,(\mu_0\,H^2 + \varepsilon_0\,E^2) \tag{1}$$

where H and E are the rms values of the magnetic and electric field respectively. Further, on the surface of a dense plasma $\varepsilon_0\,E^2 \ll \mu_0\,H^2$ in most cases of practical interest. Hence, eventually:

$$n\,k\,T = p = \beta\,\frac{\mu_0\,H^2}{2} \tag{2}$$

where $\beta \leqq 1$. For $\beta = 1$, a magnetic flux density $B = \mu_0 H$ of 0.5 Wb/m^2 is required to contain a plasma pressure of 1 kg/cm^2. Hence, for the containment of plasmas for controlled fusion, magnetic fields between 1 and 5 Wb/m^2 seem required, *provided that β be not much smaller than unity.* Such orders of magnitudes, to be maintained for seconds, seem possible for d-c magnetic fields but look most discouraging for r-f fields because of prohibitive skin effect losses in the conductors associated with the generation of these fields [3, 4]. For this reason, only little attention has been given so far to the use of r-f fields for plasma containment.

There are, however, important limitations to the use of d-c magnetic fields. The most fundamental one seems to be the inability for d-c magnetic fields to provide quasi-stable plasma containment with low enough rates of plasma leakage, for finite values of β. It is illustrative for that matter to observe that after close to one decade of work, the largest time over which a dense plasma ($n \leqq 10^{14}$) has been contained by quasi-dc magnetic fields (variation of magnetic field slow compared to plasma containment time) at temperatures of interest for controlled fusion ($T \leqq 25$ keV) is of the order of 10^{-3} s only. (Typical half-life of plasma: $2 \cdot 10^{-3}$ s.) Further, the value of β in these experiments did not exceed 0.08. This rather basic limitation of d-c magnetic

[1]) Refer to the Bibliography at the end of the article.

[2]) In a proposal by *W. I. Linlor* [1959 Meeting of the American Physical Society (A.P.S.), Paper C-1] it is shown that in a plasma-target fusion machine the target temperature could perhaps be reduced somewhat below 10 keV, with a corresponding reduction of the total pressure of the plasma to be contained. Even in this case, however, the plasma pressure will most probably have to be at least between 1 and 10 atmospheres.