AN EXPERIMENTAL BROAD-BAND HELIX TRAVELING-WAVE AMPLIFIER FOR MILLIMETER WAVELENGTHS

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Introduction

This paper considers a number of problems which have been encountered and solved in the design and construction of an experimental millimeter-wave amplifier using a microscopic helix only 0.015" in diameter. Amplifications of as much as 19 db have been obtained at a wavelength of 6 millimeters, and amplifications of 9 db have been measured at wavelengths as short as 5.2 millimeters.

As an amplifier, a helix tube offers some attractive possibilities. It promises a much greater bandwidth than can be expected with the spatial harmonic devices now contemplated.[1] Moreover, a helix tube with a well-focussed cylindrical electron beam and low interception offers the prospect of a lower noise figure and perhaps a higher efficiency than spatial harmonic tubes where the circuit is flooded with electrons, many of which are intercepted by the circuit and lost. Interception tends to increase the noise figure and lower the efficiency.

Preliminary Considerations

In order to realize the maximum amplification from a helix amplifier it is generally desirable, with a selected beam voltage, to choose the helix radius a so that γa, the helix circumference in beam wavelengths, will be about 1.25. If γa is very much larger than this preferred value, the maximum gain will occur at a frequency lower than the operating frequency. Moreover, if the feedback loss at the lower frequency is less than the maximum gain, the tube may oscillate.

For operation with a 1000 volt electron beam in the 5 millimeter region, a tube of optimum design would require a helix having an internal diameter of only 0.005". It appeared that it would be extremely difficult, if not impossible, to wind a helix of this size and keep its axis straight enough that an electron beam could be projected through it with low interception. It was also doubtful that sufficiently close mechanical tolerances could be maintained in an electron gun to produce the necessary beam for such a helix.

As a practical matter, one must compromise between the factors of size, ease of construction and performance. One is forced to use a helix of larger than the usual "optimum" diameter, and an electron gun and focussing arrangement that are very small compared with conventional practice. Moreover, one must attain an unusually high current density in the electron beam.

At the outset of this investigation it was not known how small a helix could be built or how small an electron beam could be produced. Experience with a tube developed by J. B. Little[2] had shown that a helix 0.030" in diameter could be built and used in a 6-millimeter traveling-wave tube. Intuitively, it was felt at the beginning that one might succeed in building a tube with a helix diameter of 0.015", which would have a value for γa of 4, instead of the 6.7 for Little's 0.030" helix. This would result in a substantial increase in gain and, since the tube would be operating nearer the region of maximum gain, the suppression of undesirable oscillations would be easier.

The prospect of producing a very small diameter electron beam and maintaining it in cylindrical flow of the Brillouin type appeared to be even more difficult than the problems associated with the helix. It was therefore considered desirable to experiment with small diameter, high density beams. Experimental work was initiated on the production of a 0.020" diameter beam with the thought that, if this were successful, the attempt would then be made to scale down the gun to produce a 0.010" diameter beam for the 0.015" helix.

The Electron Beam

The 0.020" Diameter Beam

Figure 1 shows a cross section of the apparatus used in the investigation of Brillouin flow of a 0.020" diameter electron beam through a 0.030" diameter drift tube 1.6 inches long. The gun is of the Pierce type and consists of a thoria-coated molybdenum cathode 0.100" in diameter, together with the appropriate beam forming electrode and anode. The gun was expected to deliver a beam of electrons having a minimum diameter of 0.020". With an anode potential of 1000 volts, the beam current was expected to be 10 milliamperes. The cathode is heated by electron bombardment by means of an auxiliary filament mounted behind the cathode.

As shown in the figure, the gun is embedded in a magnetic pole piece of cold-rolled steel. The design provides that the theoretical position of the minimum beam diameter shall be located at a point along the axis a short distance beyond the point where the electrons emerge from the hole in the anode and enter the magnetic field.

Upon leaving the 0.030" aperture in the gun anode, the beam enters the drift tube. At the far end of the drift tube is the other magnetic pole piece with a hole in the center to collect the beam. The 7-inch diameter magnetic pole pieces are vacuum sealed with neoprene gaskets to the block which supports the drift tube. The collector pole piece and the drift tube are insulated from the main housing so that the currents to these electrodes can be measured.

Extremely close mechanical tolerances were maintained on the various parts in order that the two pole faces would be accurately flat and parallel to one another, and that the axis of the hole in the drift tube would be perpendicular to the pole faces. The 90° prism shown in the figure enables an observer in front to "look around a corner", through the hole in the collector, and down the axis of the drift tube to the gun. This feature is of considerable help in checking the accuracy of alignment of the structure. By observing through a telescope, one may obtain a magnified view along the entire axis.

The entire gun tester assembly is located between the poles of a large electromagnet. Magnetic flux passes from the poles of the magnet to the tube pole faces through the hollow magnetic shunts, shown in the figure. Tests on the uniformity of the magnetic flux density between the pole faces indicated a deviation of less than 0.1% along the axis.

A number of experiments have been performed with this apparatus. The best results which have been obtained are tabulated below:

Anode voltage	1000 volts
Cathode current	10 ma
Cathode current density	200 ma/cm^2
Collector current	7.4 ma
Gun anode current	1.86 ma
Drift tube current	0.74 ma
Cathode-to-collector efficiency	74%
Drift tube efficiency	91%
Magnetic field	1400 gauss

Attention is called to the fact that the magnetic field of 1400 gauss required for best drift tube efficiency is more than twice the theoretical value of 580 gauss for Brillouin flow. This result conforms with the experience of other workers with beams of larger diameter.

The 0.010" Diameter Beam

The above results were thought to be sufficiently encouraging to warrant the scaling down of the gun by a factor of two in order to study the problem of electron flow in a beam only 0.010" in diameter. With the same anode potential of 1000 volts, the cathode current would remain at 10 milliamperes.

Before scaling, however, it seemed advisable to recheck the gun design in an electrolytic tank in order that the dimensions might be as accurate as possible. This resulted in a few minor changes in some of the electrode dimensions. It will be evident that the newer design has a slightly lower perveance. The new gun was likewise incorporated in the assembly structure shown in Figure 1. The substitution of a new drift electrode having a 0.015" diameter hole 1.6 inches long was the only other change made in the original gun tester.

The best results obtained with the 0.010" beam are tabulated as follows:

Anode voltage	1000 volts
Cathode current	8.5 ma
Collector current	6.0 ma
Gun anode current	2.1 ma
Drift tube current	0.4 ma
Cathode-to-collector efficiency	71%
Drift tube efficiency	94%
Magnetic field	1500 gauss

Attention is called to the fact that the current density in the drift tube was of the order of 10 amperes per square centimeter. Considerations of the haziness of the beam boundary in the drift tube due to the presence of thermal electron velocity components suggests that the transmission efficiency for the present beam and drift tube diameters may be near an inherent upper limit.

The Helix

The encouraging results obtained with the 0.020" beam provided the impetus to go ahead at once with the design of an amplifier with a 0.015" diameter helix, since it then appeared reasonable to expect that a 0.010" diameter beam could be produced and maintained in a reasonable approximation to Brillouin flow. Accordingly, the design of the r-f portion of the tube proceeded concurrently with the work on the 0.010" gun.

The helix dimensions were essentially determined by the beam voltage and diameter. The only dimension remaining to be chosen was the wire diameter. For reasons of mechanical strength and the ability to absorb power without overheating, the wire size was chosen to be as large as possible. A diameter of 0.002" was finally selected. The various dimensions and parameters relating to the helix are summarized in the table below:

Inside diameter	0.015"
Outside diameter	0.019"
Turns per inch	300
Length of helix	1.5 inches
Pitch of helix, p	0.0033"
Wire diameter, d	0.002"
d/p	0.6
Beam velocity	c/16 (1000 volts)

At a wavelength of 5.4 millimeters the above helix possesses almost exactly four turns of wire per wavelength. On page 40 of "Traveling Wave Tubes", Pierce gives a curve for the transverse impedance of a helix having four turns per wavelength as a function of the wire diameter-to-pitch ratio. For the present helix this impedance is found to be 72 ohms. A curve is also given for a two-turns-per-wavelength helix. Applying the data to this curve one finds that at 2.7 millimeters the helix would have an impedance of 82 ohms. This suggests that the transverse impedance does not vary rapidly with wavelength, a fact which will assume considerable importance when the problem of impedance matching at the input and output is considered.

The above data are sufficient for the computation of the over-all electrical performance of the tube including the cold loss, gain, and noise figure.

Calculated Performance

The cold loss was computed by the equation

$A = 4.35\ R/Z_o$ db per foot of helix wire,

where Z_o is the transverse impedance of the helix as defined by Pierce, and R is the high frequency resistance of the helix wire in ohms per lineal foot. For tungsten wire the computed loss for the present helix is 40 db at 5.4 millimeters. For a copper helix the corresponding value would be 22 db. The losses of a tungsten helix over a range of wavelengths were computed and are plotted in Figure 2.

The gain of the tube was calculated for beam currents of 1 milliampere and 10 milliamperes, respectively, by means of Cutler's[3] nomograph. Curves of gain vs λ are also plotted in Figure 2. The assumed values for the ratio of the actual-to-ideal circuit impedance K_2/K_1 and the ratio of the beam-to-circuit radii a_1/a were arrived at after consultation with people experienced in helix tube design at longer wavelengths, but are recognized to be possible sources of error. Higher values of a_1/a would cause the maximum gain to occur at a wavelength closer to the operating wavelength. In making the computations, it was assumed that the beam voltage remained at 1000 volts over the entire range of wavelengths and that the velocity of the wave along the helix also remained at a constant value of approximately 1/16 the velocity of light. In practice, of course, the wave velocity will be greater at the longer wavelengths which, for a fixed beam voltage of 1000, will reduce the indicated gain at these wavelengths. A curve which shows how the phase velocity varies with wavelength is also plotted in Figure 2. It was expected that in the regions where the calculated gain is in excess of the cold loss the wave velocity would be sufficiently out of step with the beam velocity, so that the possibility of unwanted oscillations at the longer wavelengths would be reduced. It was also expected that long wave oscillations might also be suppressed by placing loss material near enough to the helix to increase the long wavelength losses without substantially increasing the losses at the operating wavelength.

Noise Figure

Calculations were also made of the noise figure using the theory developed by Watkins[4] and others. Only the results will be stated here. With a beam current of 10 milliamperes at 1000 volts and with optimum spacing between the gun anode and the beginning of the helix, the computed noise figure is 29.3 db. With a beam current of 1 milliampere at the same voltage as before the noise figure is 25.6 db. In either case the noise figure is not critical with respect to the anode-to-helix spacing because of the high values of QC. These calculations neglected the effect of partition noise.

If lower noise figures are to be obtained, it will probably be necessary to use a velocity-jump arrangement in the gun, perhaps similar to that described by Watkins.[4]

R-F Coupling to the Helix

It has already been pointed out that the transverse impedance of the present helix is 72 ohms at 5.4 millimeters and that the impedance appears to change rather slowly with wavelength. Since 72 ohms is a convenient value for the impedance of a coaxial line, the possibility of connecting a 72 ohm coaxial directly to the end of this helix was immediately apparent. There was a question, however, as to whether the transverse impedance as defined for the helix corresponded to the coaxial line impedance. There were also questions of the effect of the geometrical discontinuity at the junction of the coaxial center conductor and the helix. The problem of a satisfactory mechanical support for the helix also remained to be solved.

Figure 3 shows the configuration which was finally evolved for the millimeter-wave tube. As shown in the figure, the helix is supported in a cylinder of quartz. The cylinder is made in two halves with the inside surfaces milled as shown so that the helix is supported by line contact with the four inside corners. Lavite supports were used in some of the earlier experiments, but the r-f losses due to their presence were found to be of the order of 10 db, and they were abandoned. The effect of the presence of the quartz dielectric upon the phase velocity and impedance of the helix was calculated and found to produce no more than a 5% reduction for either.

As shown in the figure, the helix and its quartz support are mounted in an accurately machined hole in an aluminum block which serves as a part of the vacuum envelope. The coaxial-to-helix connection is rather simple in geometry. The central conductor of the 72-ohm coaxial line is linearly tapered from its nominal diameter of 0.018" to a diameter of 0.002" in a length of 0.035". The purpose of the taper is to avoid an electrical discontinuity at the point of connection with the helix which would arise from the capacitive loading of the first few turns of the helix if the end of the central conductor were blunt.

In the millimeter wave tube, standing wave ratios of as low as 1/2 db have been measured in the external circuit. These measurements include the effects of the tapered bead coaxial vacuum seals and a coaxial-to-waveguide transition outside of the tube.

The quartz helix support has the additional feature of providing a simple means for adding loss along the helix in order to suppress oscillations. It was found necessary to introduce 0.013" diameter ceramic rods coated with aquadag in the longitudinal slots near the helix. At longer wavelengths the fields extend out from the helix to a greater distance and more energy is lost in the resistive coating on the rods.

The Tube Assembly

The various elements previously described were assembled into a demountable tube for testing. The gun assembly and magnetic pole structure were the same ones used in the gun tester of Figure 1. The drift tube used in the gun work was replaced by a block of aluminum containing the helix and the coaxial input and output coupling circuits. The assembled amplifier is shown in cross section in Figure 4. Figure 5 is a photograph of the complete tube ready for pumping. This figure also shows the waveguide terminals used outside the vacuum envelope for coupling the tube to the r-f measuring equipment. The coaxial lines from the tube are coupled to the waveguides by means of a simple form of transition brought to the author's attention by H. T. Friis. The coaxial central conductor extends across a low impedance waveguide whose height is only 0.010". One end of the guide tapers up to the normal RG98U waveguide dimensions. The other end contains a movable shorting piston for adjusting the impedance match. Since the central conductors are insulated from the waveguides by means of r-f chokes, the d.c. terminals of the helix are available for measuring intercepted beam current and the helix resistance.

The complete amplifier assembly was mounted between the pole pieces of a large electromagnet and connected to a high vacuum pump.

Testing the Amplifier

The measuring equipment used for testing the amplifier is shown in Figure 6. The equipment consists of a type QK289 reflex oscillator operating in the wavelength range of 1.04-1.2 centimeters. The oscillator drives a crystal harmonic generator which delivers approximately one milliwatt of second harmonic power. The millimeter wave power goes through a conventional calibrated waveguide attenuator and wavemeter before being applied to the tube. A waveguide switch by means of which the tube can be switched in and out of the measuring circuit is used for making measurements of amplifier gain. The output of the switch is connected to a conventional low-level crystal detector. When the repeller potential of the 1 centimeter oscillator is swept at a rate of 3000 cycles, a 6000 cycle signal appears at the detector output, which may be amplified with an a-f amplifier, and displayed on the cathode ray oscilloscope. If the beam voltage of the helix amplifier is then swept at a 60 cycle rate, it is possible to trace the amplifier gain vs the beam voltage characteristic on the oscilloscope. This was the form of display used in the actual gain measurements. In order to reduce the power dissipated in the tube, it was desirable at times to pulse the beam voltage with 48 microsecond pulses at a repetition rate of 1000 cycles. This had the effect of breaking up the gain vs beam voltage curve displayed on the oscilloscope into a series of pulses. The envelope could still be traced, however, and gain measurements made. A typical trace is shown in Figure 7.

Five tube assemblies have been tested. In four of the models electronic interaction was observed. However, only the last two models have given net gain.

Model 1 used a tungsten helix with no aquadag-loaded rods to suppress oscillations. It had a cold loss of 40 db and exhibited 21 db of electronic interaction with about 1 milliampere of current through the helix. It oscillated violently at a wavelength of around 8 millimeters and delivered substantial amounts of harmonic output at 4 millimeters.

Model 2 used a copper plated tungsten helix but was a failure due to a short between turns near the input end of the helix.

Model 3 had also a copper-plated tungsten helix and used one of the dissipative rods to suppress oscillations. In spite of poor cathode emission, this tube gave about 30 db of electronic interaction with only 0.4 ma to the collector.

Model 4, with a copper-plated helix, and a cold insertion loss of 35 db gave sufficient electronic interaction to reduce the measured insertion loss to 2 db. In fact, an error in the calibration of the r-f attenuator used in the measurements was later discovered, which indicated that perhaps as much as 6 db net gain had actually been obtained.

It was discovered that a relatively small amount of power dissipated on the helix was sufficient to raise the d.c. resistance and r-f losses. This was first noticed when an ohmmeter was applied to the external terminals of the helix in order to measure its resistance. The helix was in a vacuum at the time. The resistance had an initial value of 15.5 ohms which increased rather rapidly to 30 ohms as a result of the 40 milliwatts of heating power supplied by the ohmmeter. At the same time the r-f loss of the helix rose by about 10 db. The temperature rise was calculated and found to be 250° C. A calculation of the increase in loss due to the rise in resistance gave 11 db which agreed very well with the experiment. These results suggest that the fullest gain possibilities of the amplifier were not being reached because of an increase in the helix losses due to heating by the intercepted beam current. The helix was finally damaged beyond use by applying an excessive beam current.

Model 5 was then assembled and tested. No essential design changes were made but a better assembly was obtained as a result of the accumulation of experience in working with microscopic parts. For example, the spot welded joints between the ends of the helix and the coaxial lines were much smoother in this model. This resulted in excellent impedance matches at the input and output (1.5 db SWR at the input and 0.5 db at the output). In order to keep the heating of the helix at a minimum, it was decided to test this tube with a pulsed beam voltage having a duty cycle of 21.

Results obtained with Model 5 were very encouraging. Net gains of 9 to 19 db were obtained over the band of wavelengths from 5.2 to 6.0 millimeters. A curve of gain vs wavelength is given in Figure 8. The peak current through the helix was 0.84 ma. If the current were increased to a higher value, the tube oscillated at a longer wavelength. The calculated gains with an assumed current of 1 ma through the helix were in close agreement with the values measured above.

It was observed that if the r-f input power were raised to a level of about 1 milliwatt, the tube over-loaded with a power output of about 10 milliwatts and a gain of 10 db. If the input power were then reduced, the output increased.

It now appears that a beam current of 1 to 2 milliamperes will be sufficient to produce gains of at least 20 db. If the high transmission efficiency obtained earlier can be restored, the heating of the helix may not be excessive, even with an unpulsed beam.

Acknowledgment

The author wishes to acknowledge the valuable advice and encouragement contributed by numerous colleagues at Bell Telephone Laboratories. The contribution of Mr. F. A. Braun, whose technical skill played a very important part in the assembly and testing of the tube, is to be particularly noted.

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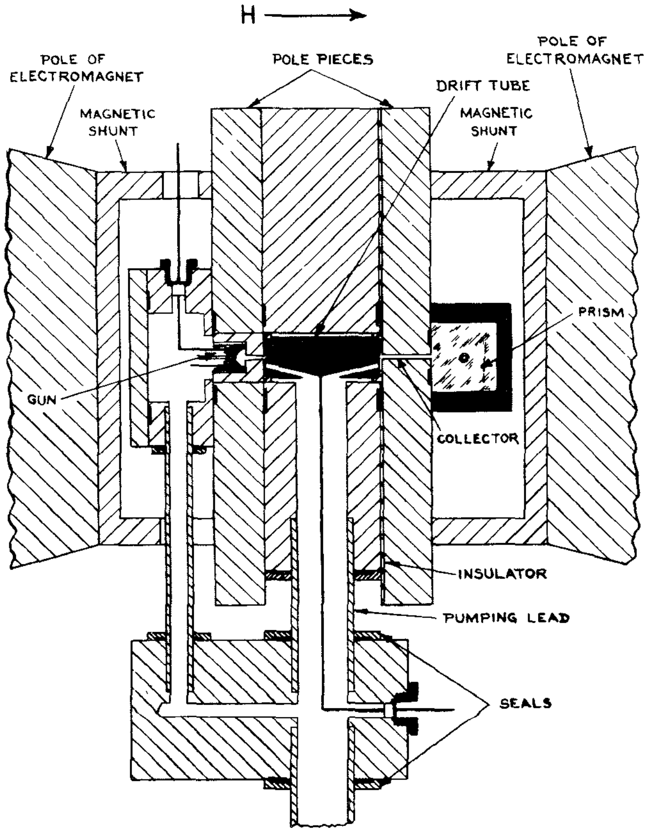

FIG. 1

GUN TESTER

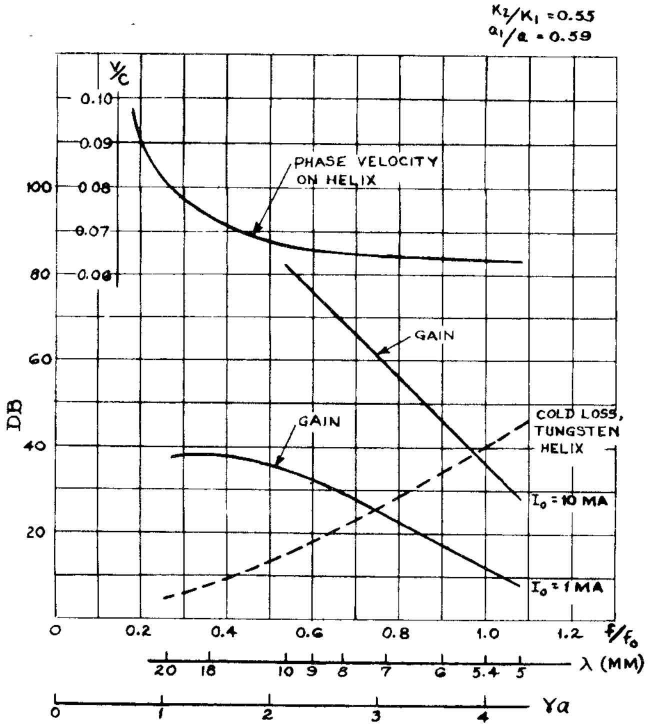

FIG. 2

CALCULATED PERFORMANCE OF AMPLIFIER

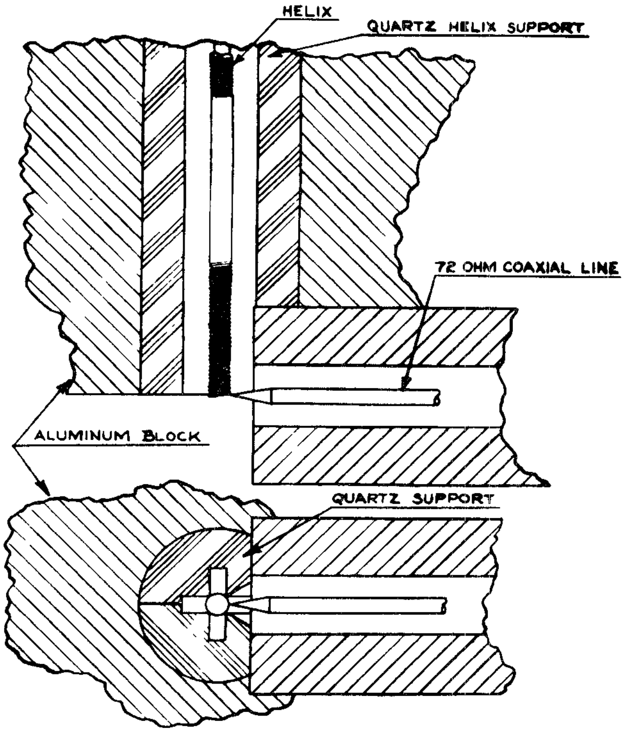

FIG. 3-COAXIAL LINE TO HELIX TRANSITION.

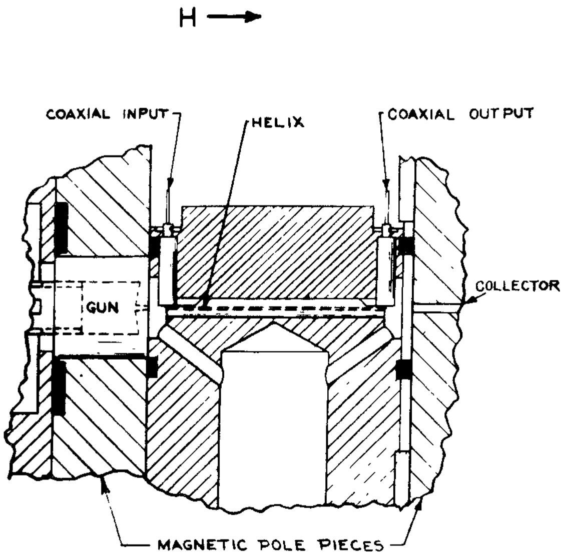

FIG. 4

ASSEMBLED AMPLIFIER

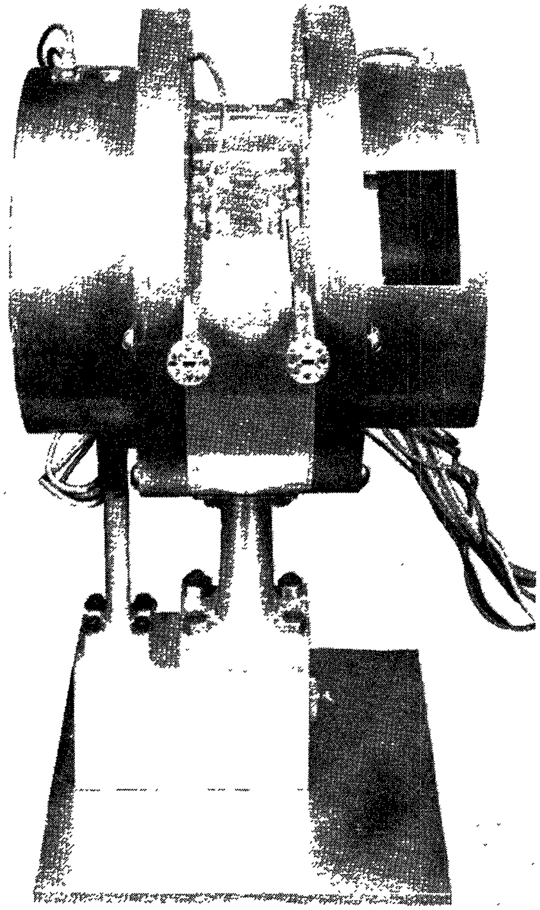

FIG. 5- EXTERIOR VIEW OF AMPLIFIER.

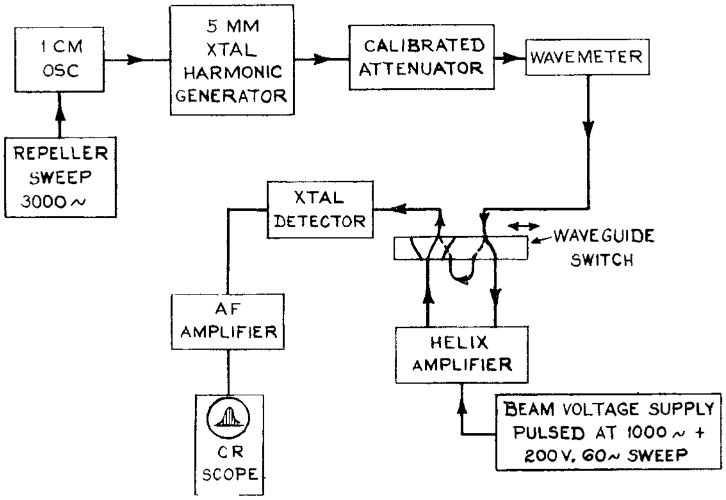

FIG. 6 - TEST CIRCUIT.

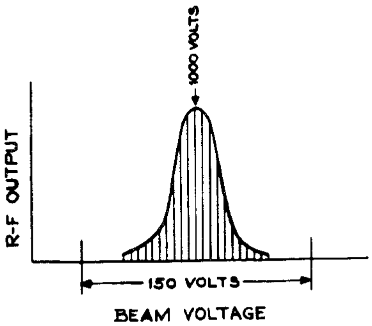

FIG. 7-AMPLIFIER RF OUTPUT VS BEAM VOLTAGE.

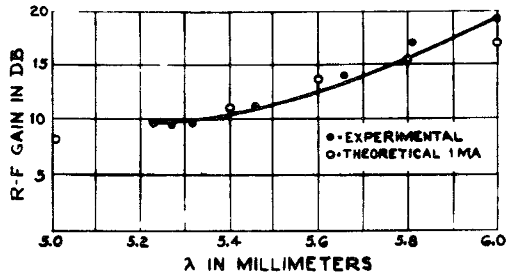

FIG. 8-GAIN OF AMPLIFIER AS A FUNCTION OF WAVELENGTH. COMPARISON WITH CALCULATED PERFORMANCE.

THE USE OF FLAT WAVEGUIDE IN THE MILLIMETER RANGE

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Abstract: The use of flat waveguide in the millimeter range has the advantage of increased power handling ability and lower attenuation as compared to the ordinary single mode guide. These advantages are gained at the expense of possible multi-mode propagation. Various flat guide components are described which are designed to operate over a 4:1 frequency band with minimum higher mode excitation. In addition, the measurement of the equivalent coupling parameters of waveguide discontinuities when two modes are propagating, is discussed. These measurements are facilitated through the use of a novel standing wave indicator which allows the standing wave of each mode to be measured separately. The experimental values of the coupling parameters are in good agreement with those predicted by theory.