A Power Amplifier for Ultra-High Frequencies *

By A. L. SAMUEL and N. E. SOWERS

A consideration of the special problems encountered at ultra-high frequencies has led to the design of a push-pull power pentode, useful as an amplifier, frequency multiplier, and modulator at frequencies of 300 megacycles per second and below. Unusual construction features include the mounting of two pentodes in the same envelope with interconnected screen and suppressor grids, complete shielding between the input and output circuits with no common leads, and provision for cooling all grids while maintaining extremely small inter-electrode spacings. The electrical characteristics depart from the conventional mainly in the low value of lead inductances and the high value of the grid input resistance at ultra-high frequencies.

The second part of the paper describes a single stage amplifier unit built for testing the tube at frequencies between eighty and 300 megacycles, and the associated apparatus for measuring input impedance, gain, and harmonic distortion. The results given indicate that by using this new tube it is possible to construct stable amplifiers at ultra-high frequencies up to 300 megacycles, having gains of twelve to twenty-five decibels per stage and delivering several watts of useful power. Stability and distortion compare favorably with those obtained from conventional tubes at much lower frequencies.

PART I—THE VACUUM TUBE

By A. L. SAMUEL

WE ARE witnessing a rapid expansion and extension in the use of radio communication. A corresponding extension in the usable portion of the radio-frequency spectrum is highly desirable. With this in mind, special forms of vacuum tubes have already been developed for use as oscillators at frequencies above 100 megacycles.[1, 2] Except at low power levels,[3] amplifier tubes have not been available.

* Presented at Institute of Radio Engineers meeting, New York City, October 7, 1936. Published in *Proceedings I.R.E.*, November, 1936.

[1] M. J. Kelly and A. L. Samuel, "Vacuum Tubes as High-Frequency Oscillators," *Elec. Eng.*, vol. 53, pp. 1504–1517, November, 1934; *Bell Sys. Tech. Jour.*, vol. 14, pp. 97–134, January, 1935.

[2] C. E. Fay and A. L. Samuel, "Vacuum Tubes for Generating Frequencies Above One Hundred Megacycles," *Proc. I.R.E.*, vol. 23, pp. 199–212, March, 1935.

[3] B. J. Thompson and G. M. Rose, "Vacuum Tubes of Small Dimensions for Use at Extremely High Frequencies," *Proc. I.R.E.*, vol. 21, pp. 1707–1721, December, 1933.

It is the purpose of this paper to discuss the problem of amplification at ultra-high frequencies and to describe one form of amplifier tube designed for moderate power in that frequency range.

The Triode as an Amplifier at Ultra-High Frequencies

A simple triode amplifier as used at low frequencies becomes unstable as the operating frequency is increased, exhibiting a tendency to oscillate or "sing" because of the interaction between the input and output circuits. This interaction or "feedback" is, in the main, produced by the grid-plate capacitance of the tube. It may be overcome either by the introduction of a compensating capacitance somewhere in the circuit or by the introduction of an electrostatic shield or screen within the tube envelope. The first expedient, known as neutralization, is employed in the case of a triode. The second expedient results in the screen-grid tetrode. At moderately high frequencies either arrangement may be used.

The conventional triode is unsatisfactory at very high frequencies. The usual capacitance neutralization scheme fails, partly because of the inductance of the tube leads which makes difficult the correct location of the neutralizing capacitance. The appreciable time required for the electrons to traverse the interelectrode spaces within the tube structure makes neutralization more difficult by introducing a shift in the phase of the necessary compensation.

A more serious effect of electron transit time is the marked increase at high frequencies in the input conductance of a tube over the value observed at low frequencies. This effect has been the subject of considerable study.[4, 5, 6, 7] Theory and experiment both agree in relating the input conductance loss to the tube geometry and the applied electrode potentials. The conductance depends upon the electron transit time and increases rapidly with increasing frequency. The transit time may be reduced either by decreasing the electron paths or by increasing the electron velocities. Decreasing the path calls for smaller interelectrode spacings, and increasing the velocity calls for higher electrode potentials. On the other hand, practical considerations limit both the dimensions and the potentials. An optimum design may utilize special mechanical arrangements to combine both expedients.

[4] J. G. Chaffee, "The Determination of Dielectric Properties at Very High Frequencies," *Proc. I.R.E.*, vol. 22, pp. 1009–1020, August, 1934.
[5] F. B. Llewellyn, "Operation of Ultra-High-Frequency Vacuum Tubes," *Bell Sys. Tech. Jour.*, vol. 14, pp. 632–665, October, 1935.
[6] W. R. Ferris, "Input Resistance of Vacuum Tubes as Ultra-High-Frequency Amplifiers," *Proc. I.R.E.*, vol. 24, pp. 82–104, January, 1936.
[7] D. O. North, "Analysis of the Effects of Space Charge on Grid Impedance," *Proc. I.R.E.*, vol. 24, pp. 108–136, January, 1936.

The electron transit time limitation becomes of particular importance at frequencies above one hundred megacycles and sets an upper frequency limit on the useful operation of the usual triode as an amplifier just as it sets the limit at which the tube will operate as an oscillator. Because of the similarity in the special high-frequency requirements, negative grid tubes designed for use primarily as ultra-high-frequency oscillators are good amplifiers at somewhat lower frequencies. The necessity for very careful circuit design and for critical adjustment of the neutralization becomes particularly pronounced when triodes are used as ultra-high-frequency amplifiers.

The Multi-element Tube as an Amplifier at Ultra-High Frequencies

Conventional screen-grid tetrodes and pentodes are also unsatisfactory at very high frequencies. Two factors are again primarily responsible, the one set by the circuit requirements, the other set by the electron transit time. These limitations will be considered in detail.

In the usual radio-frequency amplifiers using tetrodes or pentodes the input and output circuits are tuned to the desired frequency. For most practical purposes the upper limit to the frequency for which these circuits may be tuned is set by the natural period of the circuits formed by the corresponding lead inductances and interelectrode capacitances. Even before this limit is reached the major portions of the tuned circuits are within the tube envelope. Their inaccessibility makes it difficult to obtain effective coupling between amplifier stages.

Interaction between the input and output circuits if excessive may cause "singing." Such interaction is usually due to the residual value of the grid-plate capacitance. Not only must this capacitance be made very low by the proper design of the screen and suppressor grids, but its effective value must remain low at the operating frequency. This latter is realizable only if the screen and suppressor grids can be coupled to the cathode by leads having extremely small inductances. A further desirable feature is that there be no appreciable circuit impedance in the form of lead inductance common to both input and output circuits. The use of short leads is thus seen to be just as important in the design and use of the multi-element tube as it is in the design of the triode.

As in the case of the triode, the electron transit time is effective in limiting the useful frequency range of the multi-element tube. The increase in the input conductance which it introduces is again primarily responsible.

In considering the design of an amplifier tube for ultra-high frequencies, it appeared desirable to select frequency and power levels such that a break from conventional design was inevitable, leaving for future work the satisfactory coverage of the transition region. Since triodes had already been studied as oscillators it was decided to design and construct a pentode. A tentative rating of fifteen watts anode dissipation (per tube) with an operating range up to 300 megacycles was chosen. It was further thought desirable to limit the sum of the grid-to-ground and plate-to-ground capacitances to a value less than eight micromicrofarads in order to facilitate the design of the accompanying circuits.

Preliminary considerations led to the conclusion that the desired results could be best obtained by push-pull operation. In view of the required shortness of leads it seemed logical, if not essential, to inclose both sets of tube elements within one envelope and to provide an internal by-pass condenser between the screen and suppressor grids. It also appeared desirable to design the structure so that a simple extension of the screen-grid element would form a partition separating the input portion of the tube from the output portion. By mounting the tube so that the internal partition forms a continuation of the external partition separating the input and output circuits, quite adequate shielding should be possible. From previous experience, it was concluded that the special frequency requirements for a 300-megacycle amplifying tube would be satisfied by a design patterned after a 600-megacycle oscillator tube.[2]

To summarize, the following construction features were considered desirable:

(1) The mounting of two sets of elements in the same envelope.
(2) A method of interconnecting the two screen grids by a low impedance conductor.
(3) A method of grounding the screen and suppressor grids inside the tube envelope.
(4) Complete shielding between input and output sides of the tube.
(5) The use of extremely short leads.
(6) Means for maintaining very small spacings between the elements.
(7) Provision for adequate cooling of all grids.
(8) Adequate insulation paths to permit a high anode potential.
(9) The absence of any leads common to both input and output circuits.

The first of the experimental tubes designed to have a fifteen-watt dissipation per anode is shown in Fig. 1. It will be noted that a partition divides the envelope into two parts. This partition is in reality double, being made up of two sheets, one being connected to the suppressor grids and the mid-point of the filament circuit and the other being connected to the screen grids. Slots in these sheets provide space to mount the tube elements. The capacitance between the two closely

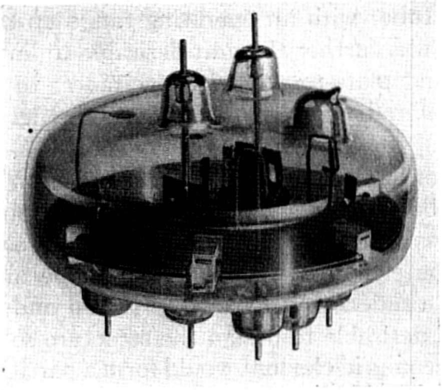

Fig. 1—An early experimental type tube.

spaced sheets forms an effective radio-frequency by-pass condenser between the screen grids and the filaments. Fig. 2 is a section view

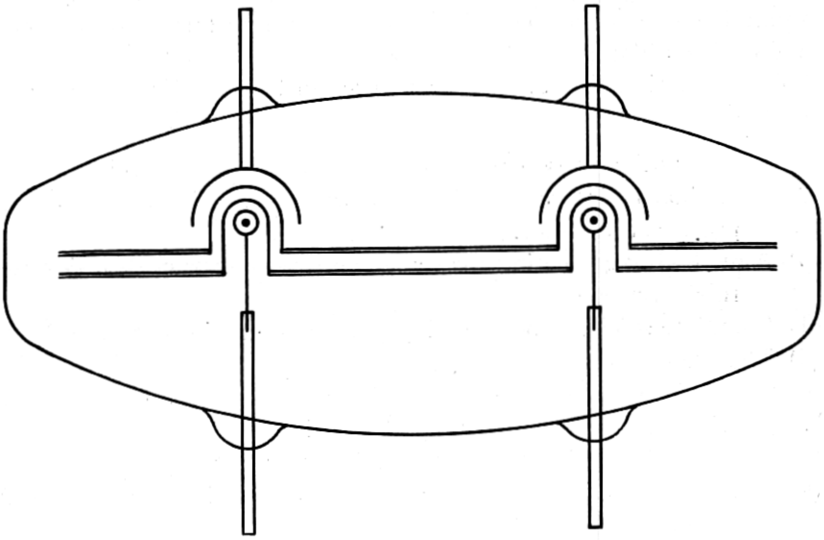

Fig. 2—Section view of the tube shown in Fig. 1.

through the middle of the tube showing the disposition of the elements. While entirely satisfactory from an operating viewpoint, this design proved to be rather difficult to fabricate.

The Ultra-High-Frequency Double Pentode Tube

The successful operation of the experimental models described above indicated the desirability of continuing this line of attack. A complete mechanical redesign to facilitate the fabrication and pumping was undertaken. Fig. 3 is a photograph of this design. Section views are shown in Fig. 4. The large capacitance between the screen and suppressor which characterized previous models was retained in the form of concentric cylinders instead of parallel plates. These cylinders and the flange at one end effectively shield the input and output sides of the tube. The low impedance connection between the two screens provided by these cylinders is an important feature of the design. Adequate cooling of the screen grid is provided by mounting it directly

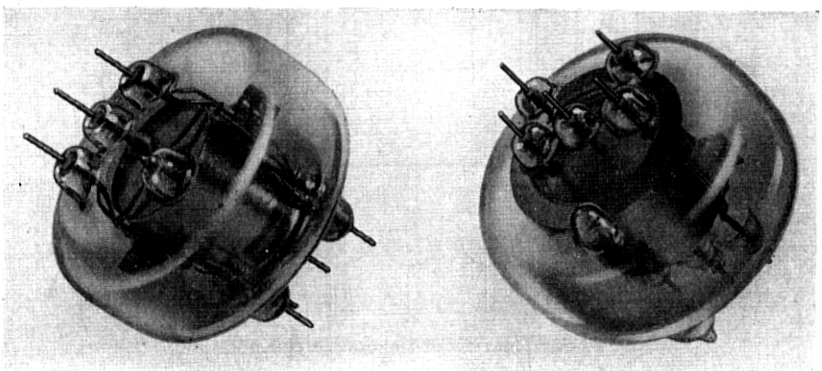

Fig. 3—The ultra-high-frequency double pentode vacuum tube.

in a slot in one of the cylinders. The control grids are of the so-called fin type of construction already employed with considerable success in triode oscillators. They consist of a series of tungsten loops attached to a common cooling fin. This construction makes feasible the use of extremely small dimensions, so that the grid-filament spacing is comparable with the filament diameter. One of these grids is illustrated in Fig. 5. The length of leads has been kept as small as is consistent with mechanical requirements. The longest lead, measured from the mid-point of its attached element to the outside of the envelope, is about three centimeters. Other details of the design are evident from the photograph and the diagram.

Operating characteristics and constants are listed in Table I.

Special attention is directed to the values of interelectrode capacitances and lead inductances. It will be observed that while the inter-

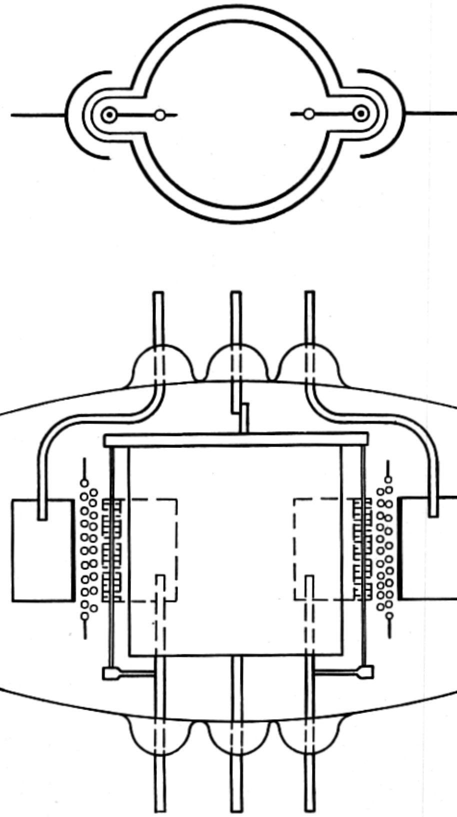

Fig. 4—Section view of the double pentode tube.

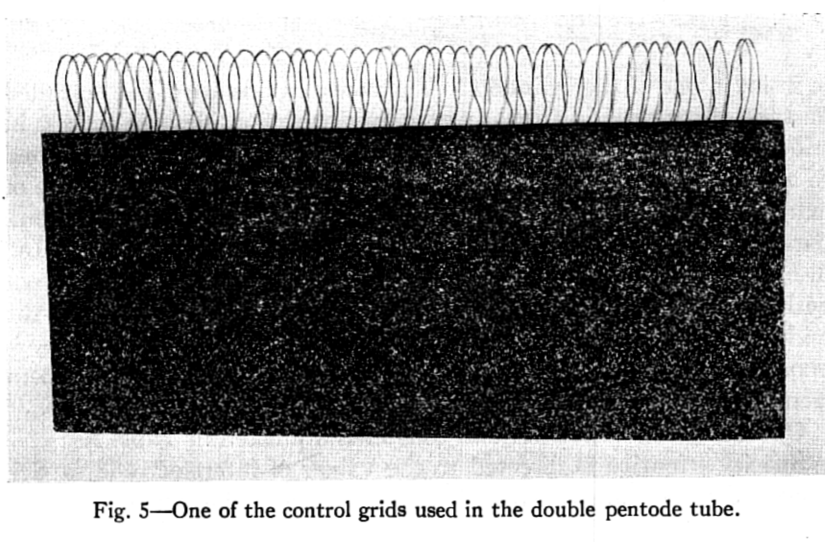

Fig. 5—One of the control grids used in the double pentode tube.

TABLE I

OPERATING CHARACTERISTICS AND CONSTANTS OF THE DOUBLE PENTODE TUBE

Filament current (each side)	5.0 amperes
Filament potential (each side)	1.5 volts
Rated anode dissipation (each anode)	15 watts
Rated screen dissipation (each side)	5 watts
At anode and screen potentials of 500 volts and anode current of 0.030 ampere—characteristics of each side	
Transconductance	1250 micromhos
Anode resistance	200,000 ohms
Normal control grid potential	−45 volts
Interelectrode capacitances (when properly mounted)	
Direct control grid to control grid	0.02 micromicrofarad
Direct plate to plate	0.06 micromicrofarad
Total control grid to ground (each side)	3.8 micromicrofarads
Total plate to ground (each side)	3.0 micromicrofarads
Control grid to plate (each side)	0.01 micromicrofarad
Lead inductances	
Total grid to grid	0.07 microhenry
Total plate to plate	0.08 microhenry
Rating as class A amplifier	
Maximum direct plate potential	500 volts
Maximum direct screen potential	500 volts
Maximum continuous plate dissipation (each)	15 watts
Maximum continuous screen dissipation (total)	10 watts
Maximum output at 150 megacycles with distortion down 40 decibels	1 watt
Nominal stage gain at 150 megacycles	20 decibels
Nominal control grid potential	−45 volts
Rating as class B amplifier	
Maximum direct plate potential	500 volts
Maximum direct screen potential	500 volts
Maximum space current (total)	150 milliamperes
Maximum continuous plate dissipation (each)	15 watts
Maximum continuous screen dissipation (total)	10 watts
Maximum output at 150 megacycles	10 watts

electrode capacitances are low they have not been reduced in proportion to the reduction in operating wave length. The more important feature is the reduction of the lead inductances. Tabulation of the value of these inductances represents a departure from the conventional practice and is made desirable by their relative importance.

A feature of the design not directly measurable under actual operating conditions but nevertheless responsible for some of the improvement over the more conventional designs is the reduction of an auxiliary dielectric material and the attending dielectric losses that occur at ultra-high frequencies.

The usual static characteristics given in Figs. 6 and 7 are seen to resemble those of the conventional pentode. For a tube which is to be used at ultra-high frequencies, certain other characteristics have a much greater significance. One of the most important of these is the active grid loss which as already mentioned comes about because of the appreciable electron transit time. Fig. 8 gives a plot of the push-pull input shunting resistance of this tube as a function of frequency. The

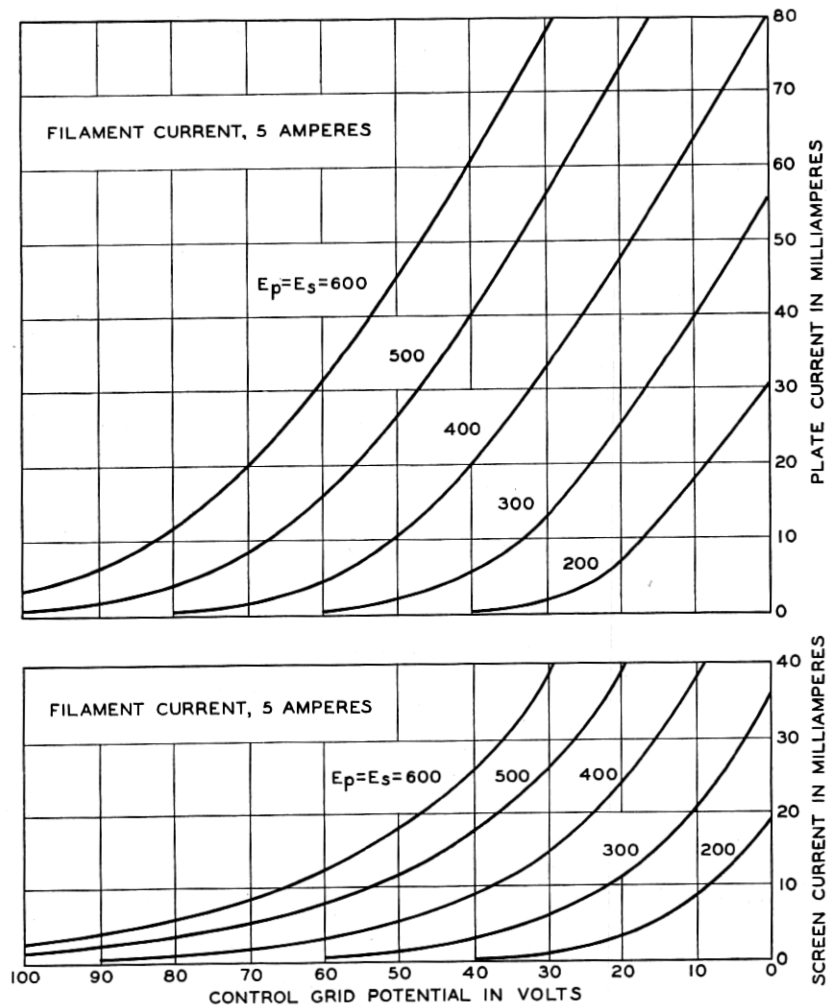

Fig. 6—Mutual characteristics of the double pentode tube.

value of 30,000 ohms at 150 megacycles is to be compared with 2000 ohms, a typical value for two conventional tubes in push-pull. At 300 megacycles the input resistance of the twin pentode is still above 5000 ohms while for conventional tubes it is so low as to make them completely inoperative. The variation in the input resistance with the operating conditions of the tube for a constant frequency of 150 megacycles is shown in Fig. 9. It is evident that if a high value of input resistance is to be realized, high anode potentials with low space cur-

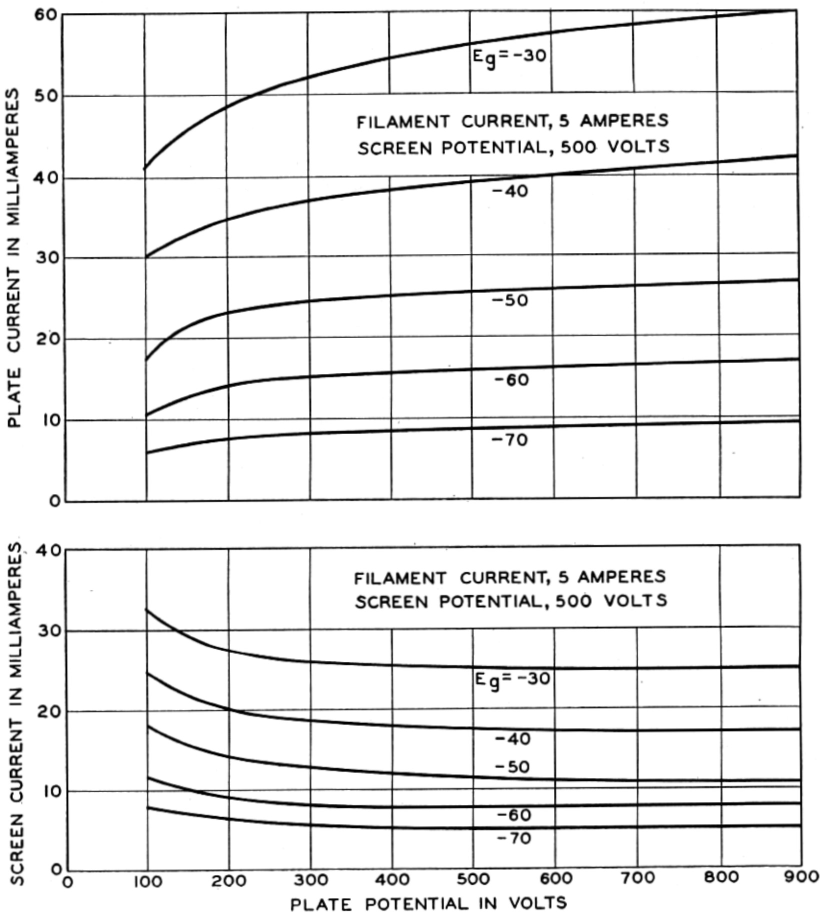

Fig. 7—Anode characteristics of the double pentode tube.

rents must be used. The reduction in the filament grid spacing made possible by the unusual construction is in a large measure responsible for the improvement in the input resistance just noted.

A characteristic measurable only at the operating frequency is the interaction between the input and output circuits which results from the residual value of the grid-plate capacitance. This reaction differs from that predicted from the low-frequency capacitance measured on a cold tube because of the inductance of the screen-grid lead and because of the electron space charge. The reaction can be measured by observing the variation in the input impedance resulting from a variation in the tuning and loading of the output circuit. Experimentally determined values are given in Fig. 10.

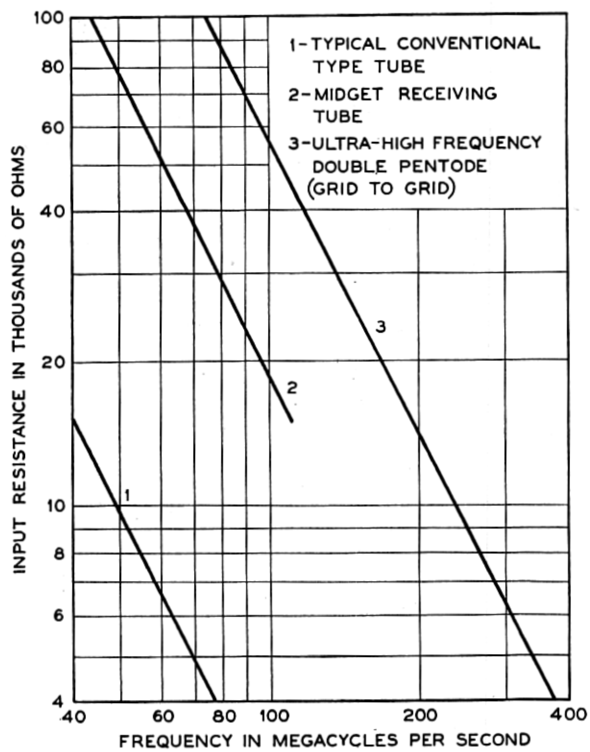

Fig. 8—The input resistance as a function of frequency.

The double pentode tube has been found useful as a high quality class A amplifier, a class B amplifier, a frequency multiplier, and as a modulator at frequencies of 300 megacycles per second and below. Its performance in these various modes of operation is quite comparable to the performance of conventional pentodes of similar ratings at much lower frequencies. Stable operation with some gain has been obtained at frequencies as high as 500 megacycles. Because of the increased importance at ultra-high frequencies of circuit design in the over-all performance of an amplifier or modulator, such tests cannot be considered as a definite measure of the capabilities and limitations of the tube but they indicate what has already been accomplished.

When operating as a class A amplifier at 150 megacycles an output of one watt is obtained with the distortion forty decibels below the fundamental. Under these conditions the stage gain is twenty decibels. Outputs of ten watts with a plate efficiency of sixty to seventy per cent and a gain of ten decibels are secured with class B operation. Experimental results confirming these statements together with a discussion of the principles of circuit design and the technique of measurements are given in the accompanying paper by N. E. Sowers.

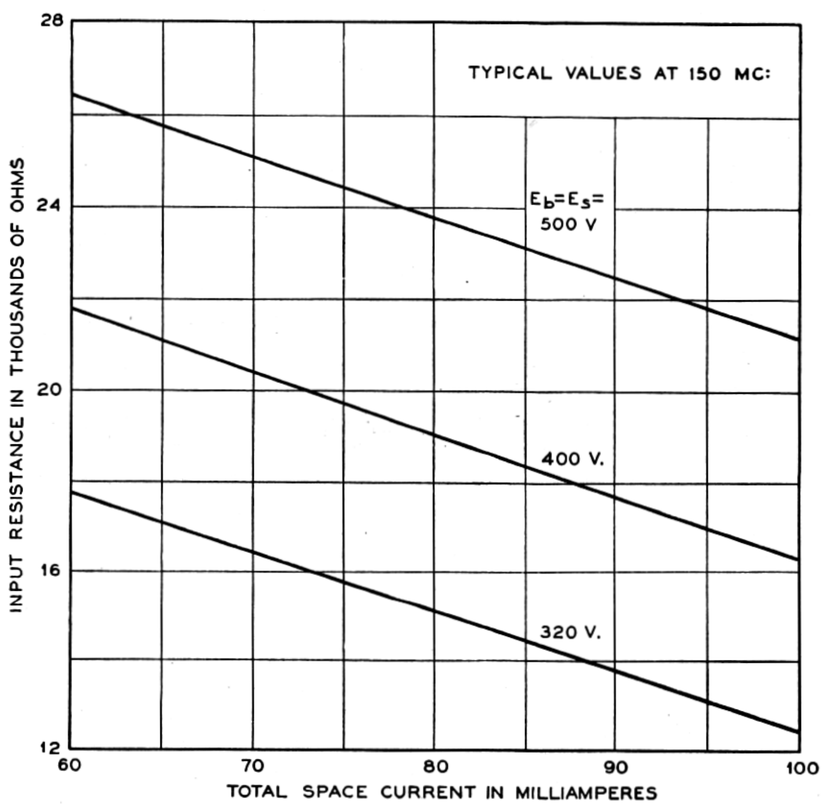

Fig. 9—The variation in input resistance with operating conditions at 150 megacycles.

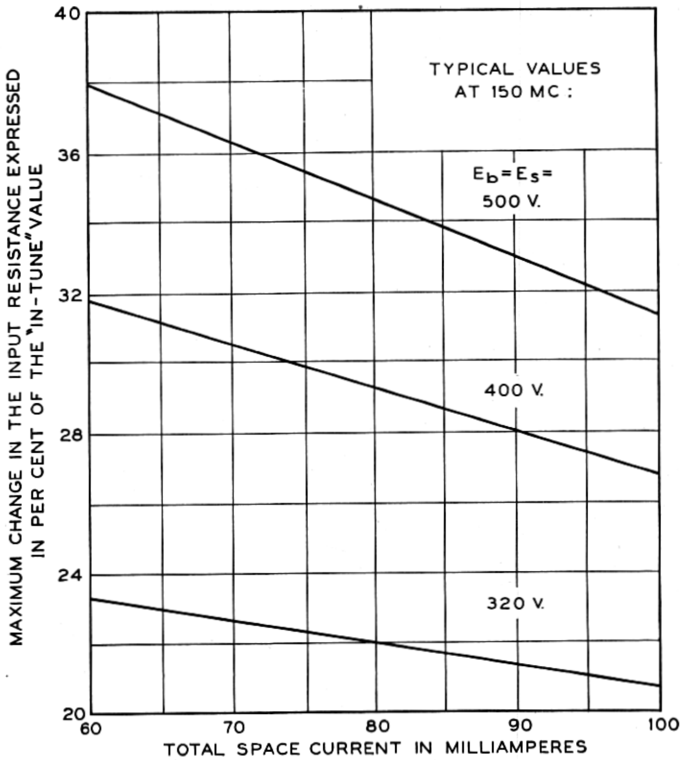

Fig. 10—The input-output reaction at 150 megacycles.

Conclusion

The development of this ultra-high-frequency pentode demonstrates that amplifier tubes of the negative grid type are usable at higher power levels and frequencies than have been reported previously. The extension of the principles underlying the design of this tube to the design of a tube with approximately ten times the output is now being considered. This type of development removes a practical barrier which has, up to the present, prevented the successful utilization of this frequency range.

PART II—THE CIRCUIT

By N. E. SOWERS

Introduction

In the first section of this paper A. L. Samuel has described the development of a push-pull pentode designed to function as a stable amplifier at frequencies up to at least 300 megacycles. It is the purpose of the present section to describe the methods and apparatus used in testing this tube and to set forth the results of some of the tests.

An attempt to study the operating characteristics of an amplifier tube at ultra-high frequencies brings up many new problems. Such fundamental properties of the tube as amplification factor, transconductance, and plate impedance do not convey as much information about the behavior of the tube at these frequencies as they do at lower frequencies. The presence of unavoidable stray inductances and capacities makes it much more difficult to separate tube problems from circuit problems. Consequently, at ultra-high frequencies we are virtually forced to consider the tube and its associated circuits as comprising a single piece of apparatus. If the circuit design is carefully made the stray inductances and capacitances can be greatly reduced in magnitude and so localized that their effects upon the over-all performance of such a piece of apparatus can, to a certain extent, be computed.

Circuit Design

Some idea of the extreme attention to detail required in designing amplifier circuits for use at ultra-high frequencies may be gained from the following considerations. Computations indicate that even with the tuned plate and grid circuits placed as close as physically possible to one of these push-pull pentodes, at 300 megacycles, the radio-frequency voltage actually applied to the grids of the tube may be as much as twenty-five per cent greater than the voltage developed across the tuned grid circuit. At the same time the load presented to the tube plates may be as much as twice the load actually present across the tuned plate circuit. These discrepancies are a direct result of the inductance of grid and plate leads which, in the case of this new tube, have already been reduced well nigh to the minimum possible.

In studying the performance of these tubes we wished to be able to check experimental results against theory at every possible point. Consequently the simplest auxiliary circuits were chosen, namely, shunt-tuned antiresonant circuits from grid to grid and from plate to plate, with screens and filaments by-passed as directly as possible to ground. In their mechanical design these circuits embody a number of features intended to reduce and localize stray inductances and capacities, into the details of which it is not possible to go at present. A simple arrangement was evolved to provide a maximum of convenience and flexibility for experimental work. The single stage amplifier unit consists of three sections, an input circuit section, a tube housing section, and an output circuit section. This arrangement permits tubes to be changed with a minimum of disturbance to the circuits. During experimental work it is almost inevitable that circumstances will arise calling for major changes in the nature of the circuits, or the size, shape, and lead arrangement of the tubes. This sectional construction provides the necessary flexibility to take care of such needs, as the construction and substitution of appropriate new sections would permit the experimental work to proceed with a minimum of delay. To facilitate the operation of several units in tandem for tests on a multistage amplifier, each section is provided with its own power supply jacks so that the only longitudinal connections required

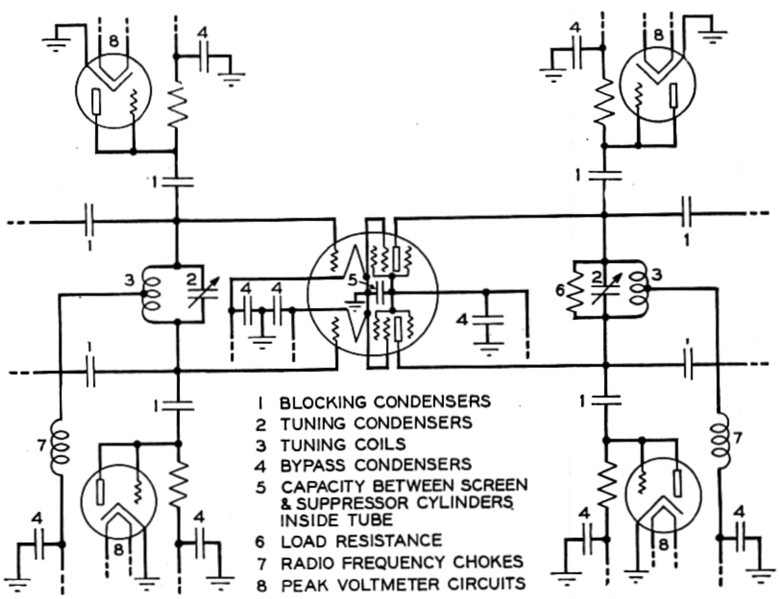

Fig. 11—Circuit diagram of single stage test amplifier.

within the sections are those between tube leads and the circuits. These connections are so arranged as to be very easily broken when sections are to be separated. Each circuit section has built into it a pair of peak voltmeters for indicating the radio-frequency voltage developed across the tuned circuit. These voltmeters consist of RCA type 955 tubes used as diode rectifiers in the familiar self-biased peak voltmeter circuit. Fig. 11 shows the circuit in schematic form. Fig. 12 shows an experimental two-stage amplifier constructed in substantially the same fashion as the test circuit, but without the sectionalizing feature.

The desire to reduce the length of all leads to a minimum has naturally resulted in bringing the tuned circuits rather close to the sides of the circuit housings. Nevertheless care and attention to

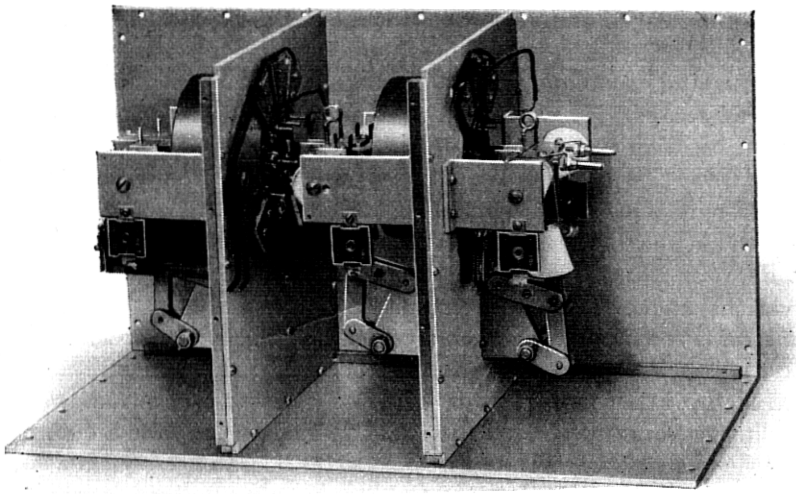

Fig. 12—An experimental two-stage one-meter amplifier using two of the earlier type push-pull pentode tubes.

detail in the circuit design have enabled the stray capacities to be kept down to satisfactory values. Fig. 13 shows in schematic form one of

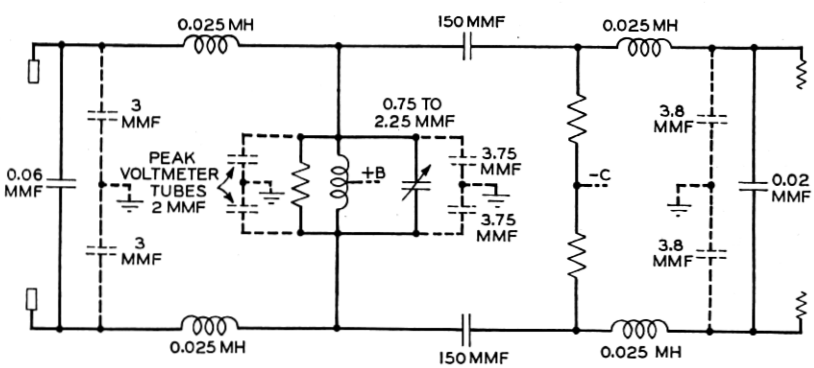

Fig. 13—Diagram of interstage circuit.

these circuits employed as the interstage circuit between two of these push-pull pentodes, all of the important inductances and capacities being included.

Input Impedance Measurement

One of the factors which effectually limits the performance of a vacuum tube at ultra-high frequencies is the internal grid resistance or active grid loss. Consequently, this factor is of extreme interest in the development of amplifier tubes for use in the ultra-high-frequency range and much of this work has centered around the development of apparatus and technique for rapidly and accurately measuring these input resistances. The method employed has been the simple resistance substitution method used by Crawford.[8]

An adjustable quarter-wave Lecher frame is provided with suitable means for inducing a radio-frequency voltage across it and a suitable detector for indicating the current flowing at the short-circuited end. A calibration is made by noting the detector indication corresponding to various known resistances connected across the open end of the frame, with the input voltage held constant. The input circuit of the tube under test is then connected to the end of the Lecher frame in place of the calibrating resistors and the detector indications corresponding to various voltages and loads applied to the tube are noted. Since the Lecher frame is initially tuned to the operating frequency, and when the tube input circuit is attached the circuit itself is retuned for resonance, it follows that the quantity actually measured is the effective resistance across the tuned circuit, including both the circuit losses and the active grid loss of the tube. It is of course possible to determine the circuit losses separately and to compute the contribution to the total resistance offered by the tube losses, and also to compute the active grid loss existing directly at the grids of the tube, taking into account the impedance transformation existing between the tube grids and the tuned circuit, brought about by the lead inductances. Practically, however, the total effective shunt resistance across the tuned circuit as actually measured is a more significant quantity, as this quantity determines more or less directly the gain which can be obtained from a multistage amplifier. It frequently happens that changes in the voltages applied to the tube produce small changes in the reactive component of the input impedance. These may be taken into account by noting the changes in grid circuit tuning required to maintain resonance. These changes are usually so small as to be of only minor interest.

The Lecher frame used in these measurements is shown in Fig. 14. The plate bridging the frame nearest the open end carries the detector, an RCA type 955 tube set into the plate. The grid of this tube is

[8] A. B. Crawford, "Input Impedance of Vacuum Tube Detectors at Ultra-Short Waves" (Abstract), *Proc. I.R.E.*, vol. 22, pp. 684–685, June, 1934.

coupled to the frame by means of a small rectangular single turn loop mounted just beneath and quite close to the bars at the short-circuited end. The second plate bridging the bars, in conjunction with the electrostatic screen between the bars and the input coupling coil, aids in

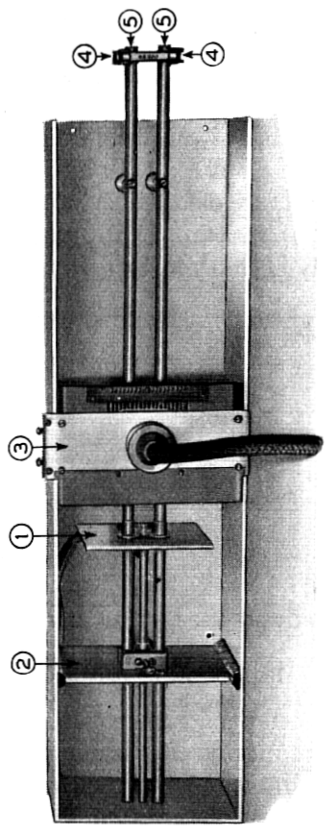

Fig. 14—Photograph of impedance measuring Lecher frame.

1. Short-circuiting bridge carrying detector tube and detector coupling coil.
2. Auxiliary bridge for breaking up unbalance currents flowing on the frame.
3. Input circuit. Note electrostatic screen between frame and input coil mounted on end of flexible transmission line leading to driving oscillator.
4. Clips carrying calibrating resistors.
5. Jacks into which plugs on amplifier input circuit fit.

eliminating any unbalance of the currents flowing in the two sides of the frame. The aluminum trough surrounding the frame provides sufficient shielding to render the apparatus virtually immune to the operator's body capacity effects. The whole resistance measuring setup is remarkably stable and satisfactory to operate. Resistance measurements on a given tube at specified operating points can be repeated with a precision of two or three per cent even when weeks elapse between measurements.

In addition to being a function of frequency, the input resistance of one of these tubes is also a function of all of the operating conditions, that is, applied voltages, plate circuit tuning, and load. In Table II are shown values of this input resistance for a typical tube at several frequencies and over a considerable range of operating conditions. Because of the large number of variables which affect this input resistance it is difficult to devise any way of plotting up these data so as to give a comprehensive picture of tube performance.

The variation of input resistance with plate circuit tuning has, for this design, consistently been of the form illustrated in Fig. 15. However, the relations between maximum, minimum, and "in-tune" values vary somewhat with frequency, operating conditions, and plate load. Also, as may be expected, they vary somewhat in different tubes which have been made up with various grid and screen spacing, etc. A convenient numerical measure of the magnitude of this reaction is obtained by taking the difference between the maximum and minimum values at any specified operating point and dividing this difference by the "in-tune" value. This reaction ratio will also be found listed in Table II for various operating conditions.

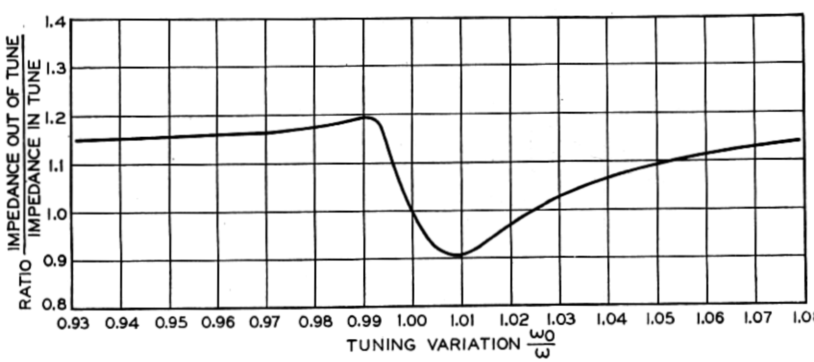

Fig. 15—Reaction curve.

Gain Measurements

The measurement of the voltage gain of an amplifier stage containing one of these tubes is a relatively simple matter. As stated in the description of the circuit, provision is made for connecting a peak voltmeter directly to each tuning condenser plate in both plate and

TABLE II

INPUT RESISTANCE AND REACTION RATIO AS A FUNCTION OF FREQUENCY AND APPLIED VOLTAGES AND CURRENTS
PLATE CIRCUIT LOAD 15,000 OHMS

		$f=150$ megacycles			$f=200$ megacycles			$f=250$ megacycles			$f=300$ megacycles		
$I_P + I_S$ mils		64	80	100	64	80	100	64	80	100	64	80	100
$E_P = E_S$ = 320 volts	resistance	17200	15050	13500	9900	8650	7750	6600	5800	5200	4900	4300	3850
	reaction ratio	0.230	0.220	0.207	0.197	0.185	0.174	0.159	0.147	0.144	0.133	0.128	0.177
$E_P = E_S$ = 400 volts	resistance	21100	19050	16250	12150	10950	9350	8150	7350	6250	6000	5450	4600
	reaction ratio	0.311	0.289	0.271	0.267	0.251	0.241	0.227	0.211	0.192	0.175	0.174	0.163
$E_P = E_S$ = 500 volts	resistance	26000	23700	21300	14950	13600	12250	10000	9150	8250	7400	6750	6050
	reaction ratio	0.373	0.346	0.314	0.324	0.298	0.273	0.270	0.257	0.232	0.216	0.207	0.190

$$\text{Reaction Ratio} = \frac{\text{(maximum resistance} - \text{minimum resistance) as plate circuit is tuned}}{\text{resistance with plate circuit in tune}}$$

grid circuits so that the applied grid drive and developed plate voltages may be read directly. Of course, the gain figure arrived at in this manner is an over-all factor, a function both of tube conditions and circuit construction and loading. Nevertheless, it is a satisfactory figure of merit for the stage. In Table III are shown these gain figures for a typical tube under various conditions.

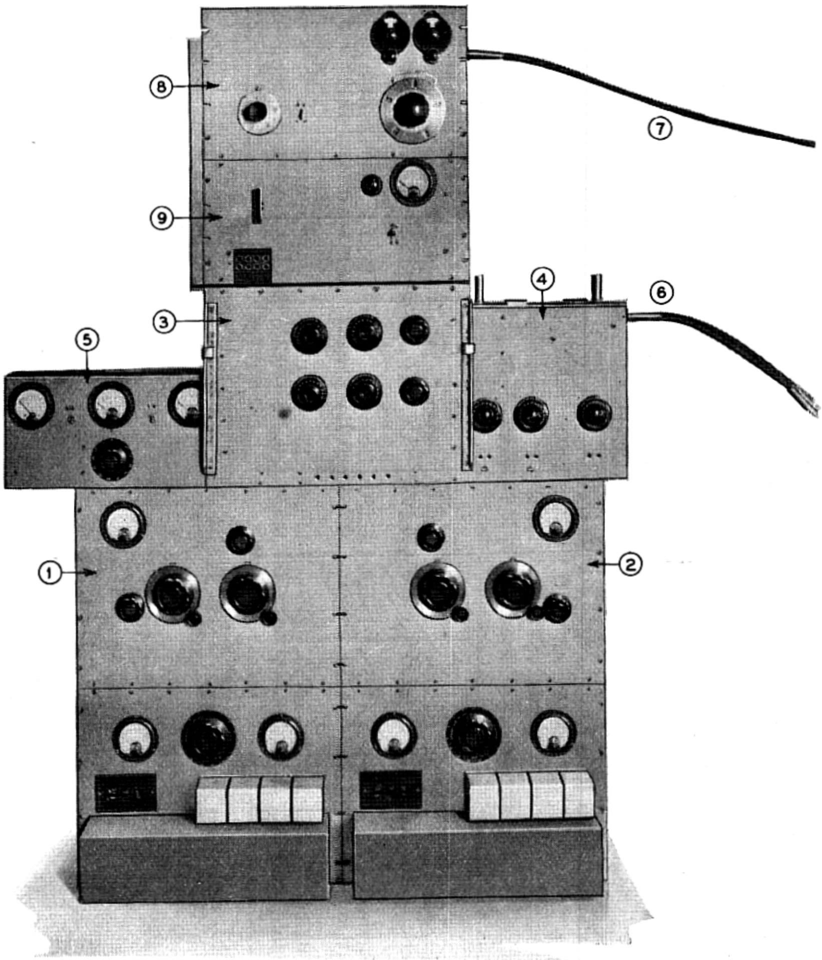

Fig. 16—Distortion measuring equipment.
Nos. 1 and 2—Signal oscillators.
3—Capacitance bridge.
4—Auxiliary amplifier.
5—Power supply unit for auxiliary amplifier.
6—Transmission lines to tube under test.
7—Transmission line from tube under test to radio receiver.
8—Beating oscillator, first detector and attenuator.
9—Intermediate amplifier and second detector of receiver.

TABLE III

STAGE GAIN IN DECIBELS AS A FUNCTION OF CURRENT, VOLTAGE, PLATE CIRCUIT LOAD, AND FREQUENCY

		$f=150$ megacycles			$f=200$ megacycles			$f=250$ megacycles			$f=300$ megacycles		
$I_P + I_S$	Mils	64	80	100	64	80	100	64	80	100	64	80	100
	Plate Cct. Load. Ohms												
$E_P = E_S$ = 320 volts	unloaded*	25.2	26.1	26.5	23.6	24.5	24.9	23.0	23.9	24.3	23.1	24.0	24.3
	15000†	18.2	19.1	19.5	17.7	18.6	19.0	18.0	18.9	19.3	18.7	19.6	20.0
	5000†	11.8	12.7	13.1	11.6	12.5	12.9	12.5	13.4	13.8	13.6	14.5	14.9
$E_P = E_S$ = 400 volts	unloaded*	24.6	25.5	25.6	23.0	23.9	24.0	22.4	23.3	23.4	22.5	23.4	23.5
	15000†	17.6	18.5	18.6	17.1	18.0	18.1	17.4	18.3	18.4	18.1	19.0	19.1
	5000†	11.2	12.1	12.2	11.0	11.9	12.0	11.9	12.8	12.9	13.0	13.9	14.0
$E_P = E_S$ = 500 volts	unloaded*	23.9	24.7	25.2	22.3	23.1	23.6	21.7	22.5	23.0	21.8	22.6	23.1
	15000†	16.9	17.7	18.2	16.4	17.2	17.7	16.7	17.5	18.0	17.4	18.2	18.7
	5000†	10.5	11.2	11.8	10.3	11.0	11.6	11.2	11.9	12.5	12.3	13.0	13.6

* Except for peak voltmeters.
† In addition to peak voltmeters.

Distortion Measurements

One of the quantities of fundamental interest in studying class A amplifiers is the amount of distortion to the applied signal generated in the tube. The technique of making distortion measurements at audio and carrier frequencies is well understood and presents no outstanding problems. However we would not expect distortion measurements made at low frequencies to have any significant application to ultra-high-frequency operation. Since the input resistance of a tube at these frequencies is obviously a function of the various voltages and currents we should expect this input resistance to vary throughout the radio-frequency cycle, that is, to be essentially nonlinear. The question of whether or not this nonlinearity is of sufficient magnitude to cause trouble can best be answered by making direct distortion measurements at the ultra-high frequencies. After some consideration of the various methods of measuring distortion we have chosen the two-tone method as being the most promising. In this method two independent frequencies suitably chosen in the transmission band of the amplifier are fed into the amplifier and the amplitudes of these two tones and such of their modulation products as are of interest are measured in the output of the amplifier by means of a suitable voltage analyzer. In the present case the "tones" are actually a pair of ultra-high-frequency signals. The principal precaution which must be taken in this method is to prevent the oscillators which supply the driving frequencies from reacting on each other and producing distortion products ahead of the amplifier under test. In the present case we have taken care of this requirement by using relatively high powered driving oscillators, very well shielded, from which only very small amounts of power are taken by means of very loosely coupled and electrostatically screened coupling coils. The outputs of the two oscillators are still further isolated from each other by connecting each across opposite diagonals of a balanced capacity bridge and taking off the voltage to drive the circuit under test across one arm of the bridge. A small amount of the voltage developed in the output circuit of the amplifier under test is picked up by a small coupling coil and fed into a voltage analyzer by means of which the relative amplitudes of the testing frequencies and their modulation products may be measured. This voltage analyzer consists of a high gain superheterodyne receiver having a rather sharply tuned, intermediate-frequency amplifier and an extremely precise tuning arrangement on the beating oscillator. The intermediate-frequency amplifier contains an attenuator which, in conjunction with the second detector current meter, permits the relative amplitude of signals to be measured.

The oscillators are push-pull tuned-plate—tuned-grid oscillators employing Western Electric type 304-A tubes with about 900 volts on their plates. These oscillators each deliver about twenty-five watts of radio-frequency power, nearly all of which is dissipated in a resistance load inside the shielding compartments. The receiver (voltage analyzer) has approximately one hundred decibels gain and a ninety-three-decibel attenuator adjustable in one-decibel steps so that measurements over a very wide range of amplitudes are possible. It was found desirable to interpose an additional amplifier (also using these push-pull pentodes) between the output of the bridge and the tube and circuits under test. Of course this amplifier introduces a possible source of distortion ahead of the circuit under test and care must be taken to operate it under such conditions that an adequate margin exists between distortion level measured at its output and distortion level existing at the output of the tube under test.

In Table IV are shown the results of distortion measurements made under several typical sets of operating conditions.

TABLE IV

RATIO OF AMPLITUDE OF THIRD ORDER MODULATION PRODUCTS TO AMPLITUDE OF ONE OF TWO EQUAL TEST FREQUENCIES

Frequency = 80 megacycles

E_P, E_S Volts	E_G Volts	I_P Mils	I_S Mils	Distortion ratio, decibels at 0.33 watt * output	Distortion ratio, decibels at 0.75 watt * output
320	−27.4	43.5	19.5	−52	−44
320	−23.8	54.0	26.0	−54	−46
320	−19.0	66.5	33.5	−56	−48
400	−38.3	44.0	22.0	−53	−44
400	−34.5	55.0	25.0	−54	−45
400	−29.5	68.5	31.5	−57	−49
500	−53.5	45.5	19.5	−57	−50
500	−49.0	56.0	24.0	−58	−50
500	−44.2	70.0	30.0	−56	−48

* For single frequency whose amplitude is the sum of the amplitudes of the two test frequencies.

OTHER APPLICATIONS

A study of the performance of these tubes as class B amplifiers, as harmonic generators, and as modulators apparently presents no serious additional problems and requires very little in the way of additional new technique. Tests indicate that in the neighborhood of 150 megacycles the performance of these tubes in such modes of operation is comparable to that of conventional pentodes in the ordinary short-wave range. In a two-stage amplifier using these tubes, with the first tube working as a class A amplifier and the second tube under class *B* conditions an output of over ten watts has been obtained with a second stage plate efficiency of around seventy per cent and with an over-all voltage gain for the two stages of twenty-four decibels. Using the first tube as a harmonic generator, driven at fifty megacycles, and the second tube as a class B amplifier, over six watts of 150-megacycle power have been obtained with an over-all voltage gain from fifty-megacycle input to 150-megacycle output of about four decibels.

Conclusions

It is often little realized how completely our present highly developed technique of making communications measurements depends upon our ability to set up stable and reliable amplifiers at the frequencies we wish to use. We are now in a position to set up such amplifiers in the ultra-short-wave range; amplifiers of sufficient gain, stability, and most important, of sufficient power handling capacity to enable us to make many of the measurements we may wish, at low enough impedance levels to minimize some of the effects of unavoidable stray inductances and capacitances in our circuits and at high enough power levels to make practicable the use of simple and reliable, and almost necessarily rather insensitive measuring apparatus. Furthermore, our experience in this work indicates that it is not necessary to modify drastically our experimental procedures when we move into the ultra-short wave field. Much more care in circuit design is required, but with more attention to details formerly unimportant, much of the background of electrical measuring technique becomes, with the advent of this new tool, available in the ultra-short-wave range.