BEAM AND WAVE ELECTRONICS IN MICROWAVE TUBES

by

RUDOLF G. E. HUTTER

Chief Engineer, Special Tube Operations
Sylvania Electronic Systems

ASSISTED BY

SHIRLEY W. HARRISON

Research Physicist
Sylvania Research Laboratories

D. VAN NOSTRAND COMPANY, INC.

PRINCETON, NEW JERSEY

TORONTO LONDON

NEW YORK

PREFACE

In the past decade or two, the magnitude of technical effort devoted to understanding the low-level behavior of microwave tubes has increased at a rapid rate. It appears, however, that a plateau is being reached and that most of the effort is now being directed either to research in the related areas of masers and parametric amplifiers or to the development of existing microwave tubes with special operating characteristics for military and commercial uses. This book was written both as a textbook for schools, so that more students will develop interests and abilities in the subject, and as introductory reading for working engineers who may have shifted their efforts to microwave-tube development. For both groups, methods of analysis have been stressed; the mode of presentation that gives only results and their interpretation has been avoided. The main purpose has thus been to give both student and worker a basic understanding of the operating principles of microwave tubes; it was not intended to write a handbook for the design engineer.

These principles have been extensively treated in the various professional publications, and many significant and original contributions have been made by workers in all parts of the world. Since these contributions vary considerably in presentation and approach, a selection of material had to be made to achieve a uniformity of presentation. This is not in any way an expression of opinion as to the originality or the significance of a particular contribution. Much of the material included here was presented in a form as close to the original as possible in order to avoid confusion when the reader turns to the reference for a more detailed discussion.

The pattern for this book was set to a large degree by an article of the author's, "Traveling-Wave Tubes," which appeared in *Advances in Electronics and Electron Physics*, Vol. VI, 1954. Large parts of this work have been included in the present book in the original form, and I wish to take this opportunity to thank Academic Press for their permission to reproduce this material. The experience gained in teaching courses in microwave-tube theory at the Polytechnic Institute of Brooklyn and at the University

of California at Berkeley was also helpful in organizing the presentation.

I would like to thank Mr. George D. O'Neill, of the Sylvania Research Laboratories, who read the original manuscript and made numerous suggestions for its improvement.

For their patience and diligence in typing a mathematical manuscript, I would like to thank Mrs. Ruth Bonn, Mrs. Marie Patane, Mrs. Katherine Gruber, and especially Mrs. Barbara Wolfe, who completed the task and assisted in the final proofreading.

Finally, I wish to express my appreciation to the Management of the Research Laboratories of Sylvania Electric Products Inc. for making it possible for this book to be published. In particular, I would like to thank Dr. R. M. Bowie, Vice President of Research, for his continuing personal encouragement and interest in the project.

R. G. E. H.

November, 1959

TABLE OF CONTENTS

Chapter 1

INTRODUCTION

1-1. The Purpose of Microwave Tubes. Ever since Hertz showed that electromagnetic waves could propagate through space and this phenomenon was utilized for communication purposes by Marconi, there have been problems of generating such waves and of detecting and amplifying signals. Practical solutions for these problems have been found for an enormous range of the frequency spectrum. Vacuum tubes such as the triode, the tetrode, and the pentode have given excellent performances at frequencies extending from the audio range to a few hundred megacycles per second. These tubes, in conjunction with passive elements such as capacitors, coils, and resistors, are still the basic components of transmitting, receiving, and other electronic equipment.

For frequencies above a few hundred megacycles per second, however, difficulties appear and special measures are required to extend the usefulness of electron tubes. At still higher frequencies, circuits as well as tubes fail, and different concepts and operating principles must be employed. New kinds of tubes—for example the klystron—depend upon electron transit-time effects which are in part responsible for the failure of conventional tubes at very high frequencies. Cavity resonators and waveguides replace the low-frequency, lumped-contsant circuits.

For a long time klystrons and magnetrons were the most commonly used vacuum tubes at frequencies from hundreds of megacycles to several tens of thousands of megacycles, a frequency range usually called the microwave spectrum. In recent years, however, there has appeared a class of microwave tubes that may be described collectively as traveling-wave tubes, a name that originated with the prototype amplifier tube, which employed a helix. Other members of the family of traveling-wave tubes are backward-wave tubes, crossed-field tubes, velocity-jump tubes, tubes whose operation is based on sudden changes of beam diameter or boundary wall, resistive-wall amplifiers, and electron-wave tubes. These microwave tubes perform the same functions as conventional tubes do, but operate in the microwave frequency spectrum. They differ from conventional tubes in that their basic principles of electronic operation are different and the microwave circuits are integral parts of the tubes.

1-2. The Contents of the Book. There are several self-imposed restrictions that limit the contents of this book. One of these is that only small-signal effects have been treated. Thus a discussion of power amplifiers and oscillators is excluded. The emphasis on fundamentals of operation justifies the brevity of treatment of klystrons and triodes.

The other main restriction has been that of space. One important subject omitted for this reason is that of the formation and control of the electron beam. This is an essential component in most of the tubes discussed in this book, and the d-c characteristics of a beam often have a bearing on the r-f performance of the device. Discussions of such effects are found at appropriate places throughout the book, but no special section on beam control has been included.

Also omitted, to prevent the book from straying from its original purpose and from becoming unduly long, are discussions of design procedures and experimental techniques. The book was not intended as a handbook for design engineers, but the reader should be able to proceed intelligently to the design of an actual tube by consulting the appropriate references for additional curves and practical considerations.

1-3. The Organization of the Material. The book begins with a brief chapter in which are discussed the limitations of conventional tubes and the difficulties encountered when attempts are made to extend their usefulness to the lower range of the microwave spectrum. This is followed by a chapter in which certain classes of microwave tubes are described schematically and the elements that the various tubes have in common are pointed out. There was a temptation to give, at this point, a description of the operation of these tubes in terms of physical pictures, since one often hears complaints that these are hard to find. It is the author's belief, however, that such physical pictures cannot be formed or appreciated without exerting the mental effort required to understand the mathematical details of the analyses of these tubes and their component elements. Indeed, in the history of the development of the theory of traveling-wave tubes, the really convincing physical pictures came late and were the fruits of preoccupation with the finer details of analysis. Only as the basic equations were worked and reworked did the pieces of the satisfying physical pictures fall into places.

Since the circuit is an integral part of a microwave tube, which is really a whole amplifier, a few chapters are devoted to microwave circuitry. The reader who is already familiar with this subject, which is treated in many excellent books, may omit Chapters 4 to 6, since these deal with ordinary microwave circuits, waveguides, and cavities. Chapter 7, however, should not be omitted; it treats the so-called slow-wave guides that are the circuits of many traveling-wave amplifiers and magnetrons, and these guides have not been discussed extensively in existing textbooks. The term *slow-wave guide* implies a guide capable of supporting waves that travel with phase velocities smaller than the velocity of light. These are the waves that interact with electron beams.

In several tubes the electron beam is acted on by r-f fields only over a short distance of its axial extent—for example, between the electrodes of space-charge-control tubes or in the gap of a klystron. In other tubes, the d-c conditions such as the velocity or surroundings of the beam may change abruptly. Chapter 8 is devoted to the r-f effects that result in either situation.

In some tubes the electron beam is permitted to drift at a constant d-c velocity for a certain distance. Impressed r-f signals become modified along the distance of travel. These changes may best be understood when it is realized that an electron beam is capable of supporting *waves*, or that characteristic qualities such as space-charge density, current density, or electron velocity can be described by means of wave functions. Once it is established that waves can exist, it is possible to develop the picture of an equivalent transmission line belonging to a wave mode on the electron beam. The combination of the results of Chapters 8 and 9 suffices to described the beam behavior of such tubes as two-cavity klystron amplifiers, velocity-jump tubes, electron-wave tubes, and resistance-wall amplifiers.

If electrons in a beam are made to travel with a velocity near that of the phase velocity of a wave on a slow-wave guide, the electrons will be under the influence of the nearly constant electric force of the traveling field wave during the whole time of their travel in the guide. Although this force may be small compared with those in the interaction gap of a klystron, its effect on the beam electrons will be large because of the extended time of action, and a wave effect will be impressed on the beam. Conversely, an electron beam so affected constitutes an impressed distributed generator in a responding waveguide, and this source will again modify the wave traveling on the circuit. It is this interplay which takes place in a traveling-wave amplifier or oscillator. Tubes using an electron beam in a longitudinal d-c magnetic field are discussed in Chapter 10, and tubes with electron streams in crossed d-c electric and magnetic fields are discussed in Chapters 11 and 12.

All tubes discussed in this book convert d-c energy into r-f energy. A detailed account of this conversion process is given in Chapter 13. It might be noted at this point that there is a whole new class of microwave amplifiers, including masers and parametric amplifiers, which convert a-c power at one frequency to a-c power at another frequency. A discussion of such devices is not, however, within the scope of this book.

It was pointed out previously that an equivalent transmission line can be found for a wave mode on an electron beam. This suggests that many microwave tubes effect a coupling of beam modes and circuit modes, and indeed this picture may be fully developed. The new light that this sheds on the operation of many of the tubes is discussed in Chapter 14. It is only in these last two chapters that an understanding is reached that can make physical pictures of operation plausible, and it is hoped that the reader will have the patience to work through the theoretical chapters preceding them.

The intention of the author—to present methods of approach leading to an understanding of the operation of microwave tubes rather than to write a handbook for the tube designer—should be most apparent in the last chapter devoted to the subject of noise. Here a method of approach particularly appealing to the author was selected for presentation. It is appealing because it is systematic and makes use of concepts developed throughout the book. It is not by any means a complete discussion of the subject of noise, and the reader who is particularly interested in this subject should consult the many other books and articles that are available.†

1-4. Submillimeter Waves. This book begins with a discussion of the limitations of conventional tubes at microwave frequencies and proceeds to describe the different concepts and operating principles that have been utilized at these frequencies. As the book was being written, it was the author's intention to conclude with a chapter in which the limitations of microwave tubes at millimeter frequencies would be discussed and the possible new concepts and operating principles described. Unfortunately, the state of the art precludes this. Although many ingenious techniques have been used to push back the upper frequency limits, no really major breakthroughs in theory have developed. Thus this subject has no place as yet in a book in which basic principles of operation are discussed.

† See, for example, *Noise in Electron Devices*, edited by L. D. Smullin and H. A. Haus, co-published by the Technology Press of the Massachusetts Institute of Technology and John Wiley & Sons, Inc., New York, February 1959.

Chapter 2

HIGH-FREQUENCY CONSIDERATIONS IN ELECTRON TUBES

The performance of conventional vacuum tubes when used as amplifiers, mixers or oscillators deteriorates at frequencies of the order of a few hundred megacycles per second, and these tubes fail to perform at all at frequencies of the order of several thousands of megacycles. Three main groups of factors contributing to the reduction of the gain of amplifiers and to the power output of oscillators will be discussed in this chapter; others will be taken up later in the book.

2-1. Electron Transit-Time Effects. Suppose that a conventional triode is first operated at low frequencies with appropriate electrode potentials and then the frequency is raised continuously while the potentials are held constant. As the frequency increases, the ratio of (a) the transit time of the electrons from one electrode to another to (b) the length of the r-f cycle, or the phase angle between the plate current and the plate voltage, will increase. When this phase angle is of the order of 1 radian, energy will be interchanged between fields and electrons while the latter are in transit and the electron stream will be velocity modulated. The resulting debunching of the stream causes a drop in the output and, at transit angles $> 2\pi$, a dispersal of the pulses of the electron stream. The input impedance decreases, a conductive component appears, and the magnitude of tube factors is reduced. To reduce the transit time and thus counteract these effects, the electrode potentials may be increased and the tube dimensions decreased. Sooner or later, however, this process will reach its limit, chiefly because the power dissipated in the tube cannot be extracted at a sufficiently high rate.

2-2. Tube- and Circuit-Loss Effects. Assume that a certain type of tube is designed for operation at low frequencies. To design a tube that will be useful for operation at higher frequencies, it is necessary to reduce all dimensions by a factor equal to the ratio r of the low frequency to the high frequency. However, this reduces the plate dissipation, if it was previously at a maximum, and also reduces the emission by a factor r^2. If the current is increased, the current density increases as $1/r^2$. Hence, the available output power decreases when the dimensions are reduced.

As the frequency is increased, the current flows more and more on the surface of conductors because of the skin effect. This results in ohmic losses in lead wires. Furthermore, lead wires become small antennas, with a resulting radiation power loss. Electrodes in vacuum tubes are usually supported by insulating material in various shapes. These materials exhibit dielectric hysteresis losses at high frequencies because of the motion of molecules under the influence of the fast time-varying fields. Radiation losses can be partially avoided by enclosing the tube in metallic shields of high conductivity or by using cavity resonators. Ohmic losses are reduced by increasing the area of lead wires or by using the disk construction characteristic of tubes operated in cavity resonators. Dielectric losses are avoided by placing insulating supports in regions of low electric field.

Losses in the lumped-constant resonant circuits increase approximately with the square root of the frequency. Since it becomes necessary to reduce the inductance of the resonant circuit at higher frequencies, the use of Lecher wires or coaxial cables is indicated. Losses in these lines can be reduced by increasing the diameter of the conductors.

2-3. Circuit-Reactance Effects. Lumped inductances and capacitances cannot be used as circuit elements at frequencies above about 1000 megacycles per second because of circuit-reactance effects. Cavity resonators and waveguides must be used and many of these new circuit elements become an integral part of the tube, inasmuch as the electrodes that control the flow of electrons form part of the circuit. This will become apparent in the course of the phenomenological description of the microwave tubes and the discussion of the theory of these circuit elements. Only a brief description of circuit-reactance effects, which limit the performance of conventional tubes, will be given here, although a considerable amount of ingenuity in tube design has extended the frequency limit of the conventional tubes. For a fuller account of these efforts, the reader is referred to other textbooks which deal with this subject.[1, 2]

The main reactance effect that exists at high frequencies is increased reactance of lead inductances. Increased electrode capacitances also become a large fraction of the capacitance required in the resonant circuit as the frequency is increased. As a matter of fact, the combination of lead inductance and interelectrode capacitance may constitute a resonant circuit at the operating frequency; a straight wire 2.5 inches long and 100 mils in diameter has an inductance of 0.05 microhenry which, together with an interelectrode capacitance of 0.5 micromicrofarad, gives a resonance frequency of about 1000 megacycles per second.

Even if resonances are avoided, lead inductances and interelectrode capacitances constitute networks between the signal source and the electrode terminals or between the tube generator and the output circuit: hence, voltages across the tube terminals will be different from those across the tube electrodes.

As an example, the input conductance of a triode will be computed, account being taken of only the cathode lead inductance L_k and grid-to-cathode capacitance C_{kg}. The following equation may be read from the circuit diagram shown in Fig. 2-1.

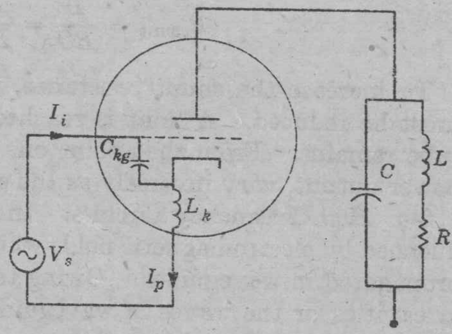

FIG. 2-1. Equivalent circuit for a high-frequency triode, showing grid-to-cathode capacitance and cathode-lead inductance.

$$V_s = \frac{I_i}{j\omega C_{kg}} + j\omega L_k I_p \qquad (2\text{-}1)$$

where V_s is the output voltage of the source, I_i is the input current and I_p is the plate current. The latter is equal to the voltage between cathode and grid times the transconductance g_m, or

$$I_p = g_m \frac{I_i}{j\omega C_{kg}} \qquad (2\text{-}2)$$

and the input admittance Y_{in} becomes

$$Y_{\text{in}} = \frac{I_i}{V_s} = j\omega C_{kg} \frac{1}{1 + j\omega L_k g_m} \qquad (2\text{-}3)$$

Since it can be shown that $\omega L_k g_m << 1$, then to a good approximation

$$Y_{\text{in}} = j\omega C_{kg}(1 - j\omega L_k g_m) \qquad (2\text{-}4)$$

and the input conductance therefore becomes

$$G_{\text{in}} = \omega^2 L_k C_{kg} g_m \qquad (2\text{-}5)$$

The cathode lead is also a part of the plate circuit, and hence the power consumed in the input conductance appears in the plate circuit. This power increases as the square of the signal frequency.

As an example of the effect of interelectrode capacitances, consider a resonant plate circuit consisting of L, C, and R as shown in Fig. 2-1. The admittance at the resonance frequency ω_0 is given by

$$Y = j\omega_0 C + \frac{1}{R + j\omega_0 L} = \frac{j\omega_0 CR}{R + j\omega_0 L} \qquad (2\text{-}6)$$

if it is assumed that $\omega_0^2LC = 1$. Furthermore, since $R^2 << \omega_0^2L^2$, this admittance is approximately equal to RC/L and the shunt resistance becomes

$$R_{\text{shunt}} = \frac{L}{RC} = \frac{\omega_0 L}{R\omega_0 C} = \frac{1}{R\omega_0^2 C^2} \tag{2-7}$$

To increase the shunt resistance, the capacitance of the tank circuit must be reduced. A limit is reached when only the capacitance of the tube remains. From that point on, the shunt resistance, and hence the power output, vary inversely as the square of the signal frequency.

2-4. High-Frequency Circuits. In microwave tubes, electrons are influenced by electromagnetic fields which are set up in cavities or which are propagated in waveguides. Owing to unavoidable losses, the oscillations in cavities or the waves in waveguides can be sustained only if power is continually introduced into these spaces from sources. The introduction is effected by a coupling arrangement the geometry of which is important in that different geometries may excite different *modes*, that is, different distributions of fields. These arrangements often consist of wire loops or short antennas protruding into the cavity or guide, or as will be shown later, they may be electron beams which have been density-modulated by a-c electric fields.

Any analysis of the fields in microwave tubes must find answers to the following questions:

1. What kinds of field distributions are possible in waveguides and cavities?
2. Which of these are excited by a given antenna configuration?
3. What happens to these field distributions when electron beams are present?

The first of these questions will be treated briefly in Chapter 4. Problems of the second kind will not be discussed at all, since many existing textbooks treat this subject.[3] The third question is the main subject of this book, since these are the very effects on which the microwave-tube operations are based.

REFERENCES

1. Reich, H. J., Skalnik, J. G., Ordung, P. F., and Krauss, H. L., *Microwave Theory and Techniques*, D. Van Nostrand Co., Inc., 1957.
2. Spangenberg, K. R., *Vacuum Tubes*, McGraw-Hill Book Co., Inc., 1948.
3. Southworth, G. C., *Principles and Applications of Waveguide Transmission*, D. Van Nostrand Co., Inc., 1950.

Chapter 3

PHENOMENOLOGICAL DESCRIPTION OF MICROWAVE TUBES

It is the purpose of this chapter to describe briefly the essential features of amplifier and oscillator tubes which operate at microwave frequencies. A great many kinds of tubes exist, and many versions of each kind. Differences between these versions will not be considered, and schematics will show only those features of each kind that are common to the many versions. This is necessary in a book which is intended as a discussion of basic operating principles of these tubes.

Among these tubes, similarities exist which make it possible to group them. Such a grouping depends on one's point of view as to which of the characteristics are important, and a choice can be made only after the operating principles have been discussed. However, the reader is asked to note a number of elements, building blocks so to speak, which some of these tubes have in common.

Most tubes employ one or more electron beams that are of greater axial length than are used in conventional tubes; r-f circuit elements, such as slow-wave guides (also called delay lines) or short gaps forming parts of resonant cavities, are located along the beam. These may be essential to the main function of the tube or may serve only as a means of coupling the signal in and out. Cylinders or disk electrodes of constant or varying inner diameter are also employed along the beam. These are held at the same or at different fixed potentials and do not support waves in the operating frequency range.

3-1. Triodes. The high-frequency triode resembles most the low-frequency tubes. The main difference between it and the low-frequency triode is that in it portions of the circuit are an integral part of the tube. However, since the spacings are made smaller in order to reduce the electron transit times between the electrodes, the physical principles of operation are the same in the microwave tubes as in tubes designed for lower frequencies.

The construction of a high-frequency triode is shown in Fig. 3-1. The grid controls in conventional manner the beam current coming from the cathode and passing on through the grid to the anode. All electrodes are planar and are thus disk-shaped. The capacitance of the gaps between the cathode and the grid and between the grid and the anode load the resonant circuit, which usually consists of a cavity formed by short sections of coaxial cylinders. These cylinders are insulated from one another so that it is possible to operate them at different direct potentials. Cavities of the type shown in Fig. 3-1 are called reentrant cavities; in this case the length may be varied by means of plungers, as shown.

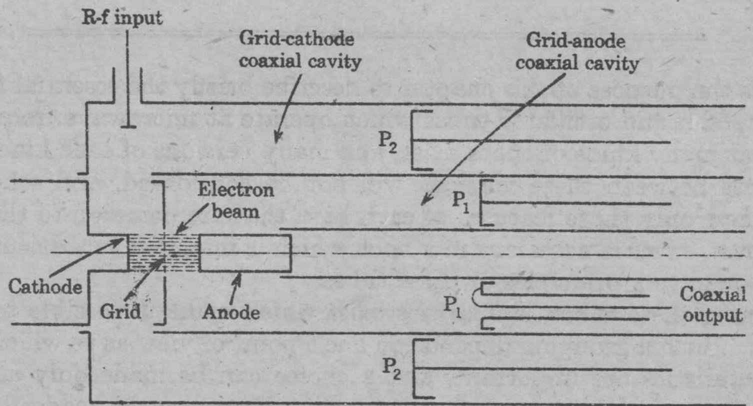

FIG. 3-1. Schematic of a high-frequency triode. The length of the grid-anode coaxial cavity can be varied by moving plungers P_1 and the length of the grid-cathode coaxial cavity by moving plungers P_2.

3-2. Klystrons. Fig. 3-2 is a schematic drawing of the two-cavity klystron. This microwave tube differs from tubes used at lower frequencies not only with respect to the circuit, but with respect to its operation as well. The important building blocks are gaps, cavities, and a drift region. An electron gun, similar to those used in cathode-ray tubes but capable of supplying higher beam currents, produces an electron beam which traverses, in succession, the input-cavity gap, a drift region, and the output-cavity gap. The electrons are finally collected by a collector electrode and returned through the d-c power supply to the cathode of the gun. A coupling scheme, one form of which is illustrated in Fig. 3-2, is used to introduce r-f power into the input cavity. The electromagnetic field established in this manner in the input cavity produces a strong alternating electric field across the input interaction gap, so that the electrons passing the gap at different parts of the cycle are differently