Section 20

MICROWAVES

Organized with the assistance of the IRE Professional Group on Microwave Theory and Techniques

Survey and History of the Progress of the Microwave Arts*

GEORGE C. SOUTHWORTH†, FELLOW, IRE

Summary—**This is a review of the history and technical progress of the microwave techniques beginning with fundamental research and continuing to present-day practical applications. Particular emphasis is placed on the evolution of techniques that are now of great practical importance. Included are the ordinary 2-wire transmission line and the useful tuning devices that it has provided and also the more recent waveguide techniques which have added not only a new medium of transmission but new antennas for radiating and receiving electromagnetic waves, and a new type of circuitry for dealing with microwaves. Reflecting discontinuities, sometimes conductive and sometimes reactive, when judiciously located inside a waveguide, may perform numerous useful functions such as matching transformers, frequency filters and special networks that very knowingly allow wave power to pass in one direction and not in the reverse. The present paper is a greatly condensed portion of certain chapters of a new book entitled "Forty Years of Radio Research."[1] The latter tells of the author's personal experiences, not only in connection with microwaves, but in connection with the development of much of the rest of the radio spectrum as well.**

INTRODUCTION

MICROWAVES represent the newest and possibly the most useful band of the entire radio spectrum. Beginning at roughly one thousand million cycles, known as one kilomegacycle (sometimes called one gigacycle) and abbreviated 1 kMc, it extends upward to a frontier now temporarily poised at about 30 kMc. These limits correspond to wavelengths of 30 cm and 1 cm, respectively. Current research extends far beyond, possibly to 100 kMc or even higher. Included in this new band are all of the known forms of electrical communications—telegraphy, telephony, television and radar.

Microwaves are characterized by various new techniques. In place of the coils and condensers of conventional radio, which upon approaching this frequency range were becoming vanishingly small, equivalent results in this new band are accomplished by properly spaced discontinuities. Also in this band, radio directivity, one of the time-honored objectives of radio engineering, is at its best. In this band too, another of the objectives of electrical communications is also at its best; that is, the transmission from one point to another, almost as a single package, of a maximum of information. For example there may be transmitted over the same facility, alternatively, either several television channels, or many hundreds of telephone channels, or a very great number of telegraph channels. Although this is the proud accomplishment of a radio system in the microwave range, there is in prospect in this same range of frequencies, a waveguide transmission line that has far wider bandwidth potentialities. Thus, in this upper register of frequencies both radio and guided

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† Bell Telephone Laboratories, Inc., Murray Hill, N. J.

[1] G. C. Southworth, "Forty Years of Radio Research," Gordon and Breach Scientific Publishers, New York, N. Y.; 1962. (350 pp. 60 Figs.)

waves may become worthy competitors for similar jobs. These and other features of this new band of frequencies will be discussed below.

It is not known for certain when the term *microwaves* originated. It is known, however, that a somewhat related term *microrayons* was used about 1933 by Andre Clavier and his associates of *Les Laboratories Le Materiel Telephonique* in describing a newly developed directive radio system for communicating across the English Channel. The frequency was about 1.75 kMc ($\lambda = 17$ cm). The available power was roughly 1 watt. Directive antennas used at each end, having power gains of 2000 (33 db), gave the 1 watt of power the effect, by ordinary radio standards of the time, of 4 kw. These directive gains are comparable with present-day microwave practice. This was a truly pioneering venture as it pointed the way to the rich rewards that come from the use of the higher radio frequencies.

BEGINNINGS OF MICROWAVES

Like radio itself, and like many other branches of electrical technology, microwaves had their origin in the fundamental electromagnetic theory. One group of mathematical physicists, bent on explaining the behavior of conventional two-wire lines, adapted the electromagnetic equations to the cases of two parallel conductors and also to two coaxial conductors. From these deductions developed much of the basic theory underlying ordinary transmission lines and also the various standing-wave phenomena now so widely used in microwave circuitry. Somewhat later, another group of mathematicians fitted the same electromagnetic equations to hollow metal pipes and to dielectric wires and, by invoking similarities with ordinary two-wire lines, they extended the theory to waveguides generally. These two techniques, coaxial and waveguide, remain as important methods for dealing with microwaves. Often the roles are complementary. Sometimes they appear in the same piece of apparatus, often in a way that makes it difficult to distinguish between the two. In recent years, a very useful microwave technique has grown from a special adaptation of two-conductor theory. In this case two flat conductors are mounted on opposite sides of a thin insulator. This is referred to as strip-line technique.

EARLY HISTORY OF WAVEGUIDES

Waveguides, as contrasted with coaxial lines, have an extremely interesting past. That it might be possible to transmit electromagnetic waves through hollow metal pipes must have occurred to physicists almost as soon as the nature of electromagnetic waves became fully appreciated. That this might actually be accomplished in practice was probably in considerable doubt, for certain conclusions of the mathematical theory of electricity seemed to indicate that, without a return conductor, it would not be possible to support inside a hollow conductor the lines of electric force of which waves were assumed to consist. Heaviside was one of the early doubters.[2]

Perhaps the first analysis suggesting the possibility of waves in hollow pipes appeared in 1893 in the book "Recent Researches in Electricity and Magnetism" by J. J. Thomson.[3] This book, which was written as a sequel to Maxwell's "Treatise on Electricity and Magnetism," examined mathematically the hypothetical question of what might result if an electric charge should be released on the interior wall of a closed metal cylinder. Even now, this problem is of considerable interest in connection with resonance in hollow metal chambers. A much more significant analysis, relating particularly to propagation through dielectrically filled pipes, both of circular and rectangular cross section, was published in 1897 by Lord Rayleigh.[4]

As regards experimental verification, it is of interest that Sir Oliver Lodge[5] as early as 1894 approached, but probably did not quite realize, actual waveguide transmission. Of much greater significance were some experiments reported a year later by Viktor von Lang[6] who repeated for electric waves the interference experiment that had been performed for acoustic waves by Quincke some years earlier. Other similar experiments were performed later by Drude[7] and Weber.[8] All these experiments were done with the damped waves from spark discharges.

In about 1913 Professor Zahn[9] of the University of Kiel became interested in this problem and assigned certain of its aspects to Schriever and Reuter, two young candidates for the doctorate. They had barely started when World War I broke out, and both left for the front. Reuter was killed at Champagne in the autumn of 1915, but Schriever survived and returned to complete his thesis in 1920,[10] using for his source the newly available Barkhausen oscillator. Schriever's work was aimed specifically at dielectric wires, and was the first to use continuous waves.

The contributions of Thomson, Rayleigh, and their followers were, of course, purely mathematical. Those of von Lang, Drude, Weber, and Schriever were experimental, but they were of rather limited scope. The con-

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[2] O. Heaviside, "Electromagnetic Theory," reprinted by Dover Publications, Inc., New York, N. Y., vol. 1, p. 399; 1893.

[3] J. J. Thomson, "Recent Researches in Electricity and Magnetism," p. 344; 1893.

[4] Lord Rayleigh, "On the passage of electric waves through tubes or the vibrations of dielectric cylinders," *Phil. Mag.*, vol. 43, pp. 125–132; February, 1897.

[5] O. Lodge, *Proc. Roy. Inst.*, vol. 14, p. 321; 1894.

[6] V. von Lang, "Interenzversuch mit Electischen Wellen," *Sitzber, Ges. Wiss. Wien, Abt. II*, vol. 104, 1895; p. 989, 1896. Wiedemann, *Ann. Physik und Chemie*, vol. 57, p. 430; 1896.

[7] P. Drude, "Über die Messung Elektrischen Wellenläugen mittels der Quickéschen Interferenzrohre," *Ann. Physik und Chemie*, vol. 65, p. 481; 1898.

[8] R. H. Weber, "Electromagnetic waves in metal pipes," *Ann. Physik*, vol. 8, pp. 721–751; July, 1902.

[9] H. Zahn, "Detection of electromagnetic waves on dielectric wires," *Ann. Physik*, vol. 49, pp. 907–933; May, 1916.

[10] O. Schriever, "Electromagnetic waves in dielectric conductors," *Ann. Physik*, vol. 63, pp. 645–673; December, 1920.

cept of the hollow pipe as a useful transmission element, for example as a radiator or as a resonant circuit, apparently did not exist at these early dates. Nothing was yet known quantitatively about attenuation, and little or nothing of the present-day experimental technique had yet appeared. At this time, the position of this new art was perhaps comparable with that of radio prior to the time of Marconi. The reader who wishes to learn more about the early history of microwaves should consult standard textbooks on the subject.[11]

LATER HISTORY OF WAVEGUIDES

The history of waveguides changed abruptly in about 1931 when it was shown for the first time that they could be put to practical use. Several patent applications were filed, and numerous scientific papers[12–15] were published. More recently, a great many papers have appeared; too many, in fact, for detailed consideration at this time.

The author's interest in guided waves stems from some experiments done while working with Lecher wires in a trough of water about 1920. In one case there were found, superimposed on the guided waves that might normally travel along two parallel conductors, other waves having a velocity that somehow depended on the dimensions of the trough. These may now be identified as the so-called dominant or TE_{11} type. Eleven years later, this work was resumed, and since that time a continued effort has been made to develop a useful technique for dealing with microwaves from fundamental principles of waveguide transmission.

The earliest experiments consisted of transmitting electromagnetic waves through tall cylinders of water. Thus, it became possible to set up, in the relatively small space of one of these cylinders, many of the wave configurations predicted by theory. In addition it was possible, by producing standing waves, to measure their apparent wavelength and thereby calculate their phase velocity. Also, by investigating the surface of the water by means of a probe, the directions and also the relative intensities of lines of electric force in the wave front could be mapped. It is probable that certain of these modes were observed and identified for the first time. Figs. 1 and 2 show the nature of this early apparatus and the types of wave configuration that were mapped. A more complete account of this early work may be found in an early article by the author.[14]

Shortly afterwards (1933), sources giving wavelengths in air of 15 cm became available, and the experimental work was transferred to air-filled copper pipes only 5 in in diameter. At this time, a 5-in hollow-pipe transmission line 875 ft in length was built, through which both telegraph and telephone signals were transmitted (Fig. 3). Measurements showed that the attenuation was relatively small.

It was recognized at an early date that a short waveguide line, with suitable modification, might function as a radiator and also as a reactive element. Most obvious were the electromagnetic horn and the resonant cavity. These properties were likewise investigated experimentally, and numerous useful applications were proposed. Descriptions of these early methods may be found in another early article by the author[13] as well as in several of the early patents. As will be noted, modern waveguide circuitry had its beginnings in the efforts to obtain a more efficient transfer of microwave power from a source to a waveguide transmission line, thereby providing the elements of a transmitter, and again the efficient recovery of the microwave power at the receiving end, thereby providing the elements of a receiver.

As might be expected, a great many people contributed in one way or another to the early success of this venture. Particular mention should be made of the very important parts played by the author's colleagues, A. E. Bowen and A. P. King, who, during its early and less promising years, contributed much toward transforming rather abstract ideas into practical working equipment, such as frequency meters, standing-wave detectors, and terminations. Much of this equipment was found to be of important military use immediately upon the advent of war. Also of great importance were the parts played by the author's colleagues, Dr. S. A. Schelkunoff, J. R. Carson, and Mrs. S. P. Meade, who, in the early days of this work, provided a substantial segment of mathematical theory that previously was missing. During the succeeding years, Dr. Schelkunoff, in particular, made invaluable contributions in the form of analyses which, in some cases, indicated the direction toward which experiment should proceed and, in others, merely confirmed experiment, while in still others, gave answers not readily obtainable by experiment alone. A particularly important result of this analysis was the discovery that, for one of the types of waves that may be propagated through a circular metal pipe of given diameter, the attenuation decreases with increasing frequency. It is expected that this principle will play a very important role in the future of microwaves.

Beginning sometime prior to 1936, Dr. W. L. Barrow, then of the Massachusetts Institute of Technology, also became interested in this subject and, together with numerous associates, made very substantial contributions particularly in the direction of determining the best proportions for electromagnetic horns. No less than eight scientific papers were published covering

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[11] G. C. Southworth, "Principles and Applications of Waveguide Transmission," D. Van Nostrand Co., Inc., New York, N. Y.; 1950.

[12] J. R. Carson, S. P. Meade, and S. A. Schelkunoff, "Hyperfrequency waveguides—mathematical theory," *Bell Sys. Tech. J.*, vol. 15, pp. 310–333; April, 1936.

[13] G. C. Southworth, "Hyperfrequency waveguides—general considerations and experimental results," *Bell Sys. Tech. J.*, vol. 15, pp. 284–309; April, 1936.

[14] G. C. Southworth, "Some fundamental experiments with waveguides," PROC. IRE, vol. 25, pp. 807–822; July, 1937.

[15] G. C. Southworth and A. P. King, "Metal horns as directive receivers of ultra-short waves," PROC. IRE, vol. 27, pp. 95–102; February, 1939.

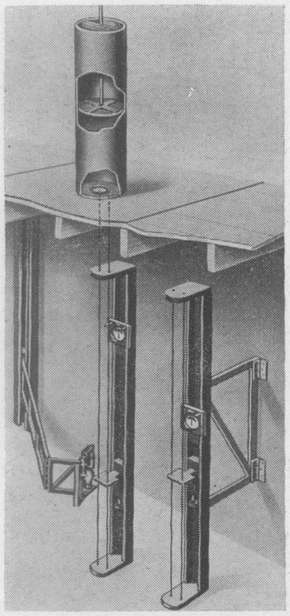

Fig. 1—Apparatus used to identify guided waves. Relative velocity and cutoff frequency were measured. A probing crystal detector and meter made it possible to identify various modes.

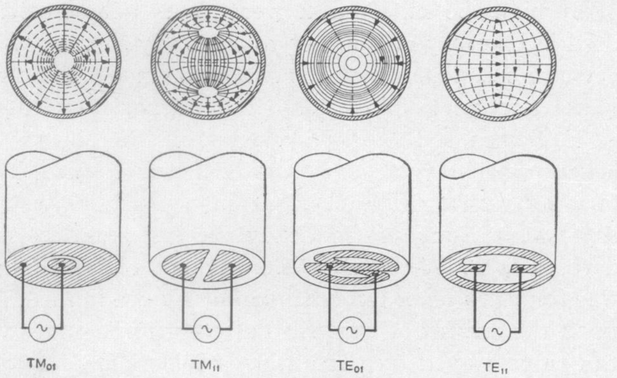

Fig. 2—Schematic of various launching devices used to set up various modes.

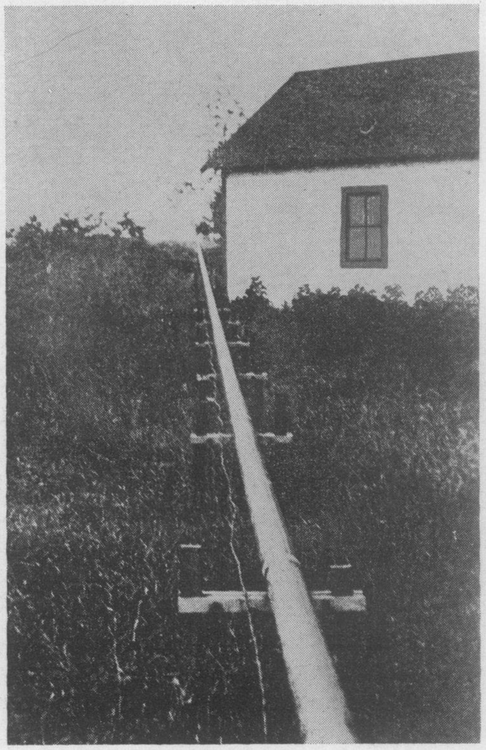

Fig. 3—A section of the first waveguide transmission line built August, 1933.

special features of hollow-pipe transmission lines and electromagnetic horns.[16–18] For several years the work at the Massachusetts Institute of Technology and at the Bell Telephone Laboratories probably represented the major portion of, if not indeed the only, work of this kind in progress, but with the advent of World War II, hundreds or perhaps thousands of others entered the field. For the most part, the latter were workers on various military projects. Beginning with the considerable accumulation of unpublished technique which was made freely available to them at the outset of the war, these workers, along with others in similar positions elsewhere in this country and in Europe, have helped to bring this technique to its present very satisfactory state of development.

MORE ABOUT THE PREWAR DEVELOPMENT

The progress made before World War II is conveyed in part by Figs. 4–9. Fig. 4 shows numerous pieces of measuring equipment fundamental to the development of microwaves. It is representative of techniques as of about 1934. Figs. 5 and 6 show a platform as it appeared for the presentation of two demonstration lectures before the IRE on February 2, 1938, and again on February 1, 1939. In the first, four of the more important modes were produced in the apparatus shown, and their orientations were plotted for the audience on a blackboard placed over the several sources. As an added feature, 3-kMc ($\lambda = 10$ cm) waves were produced and were propagated through a 3-in metal pipe and received in a loosely-coupled resonant chamber.

The second demonstration, in 1939 (Fig. 6) had two objectives. In the first objective, a match termination was developed by a step-by-step process as the audience observed the gradual disappearance of the standing wave. By this time the standing-wave detector had become a standard piece of measuring apparatus much as we know it today. The second objective of this demonstration was to plot for the audience the directive patterns of several electromagnetic horns. Both lectures were repeated before various sections of the IRE.

A third demonstration lecture was planned which was aimed particularly at reactive elements in a waveguide,

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[16] W. L. Barrow, "Transmission of electromagnetic waves in hollow tubes of metal," PROC. IRE, vol. 24, pp. 1298–1328; October, 1936.

[17] W. L. Barrow and F. M. Greene, "Rectangular horn-pipe radiators," PROC. IRE, vol. 26, pp. 1498–1519; December, 1938.

[18] W. L. Barrow and L. J. Chu, "Theory of the electromagnetic horn," PROC. IRE, vol. 27, pp. 51–64; January, 1939. Also, *Trans. AIEE*, vol. 58, pp. 333–338; July, 1939.

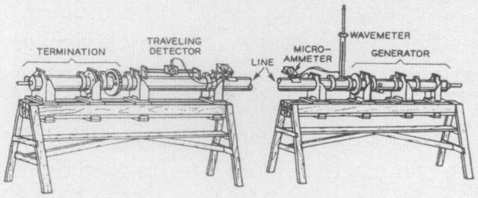

Fig. 4—Optical benches containing microwave equipment typical of 1934.

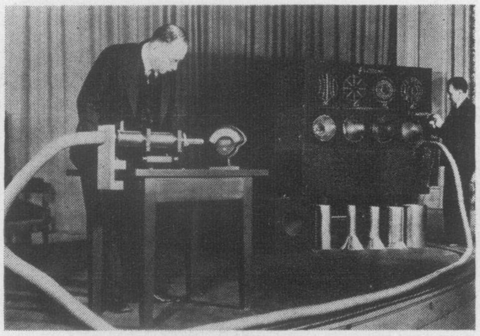

Fig. 5—First demonstration of waveguides before the IRE on February 2, 1938. This emphasized particularly, the different modes of transmission and their respective cutoff frequencies.

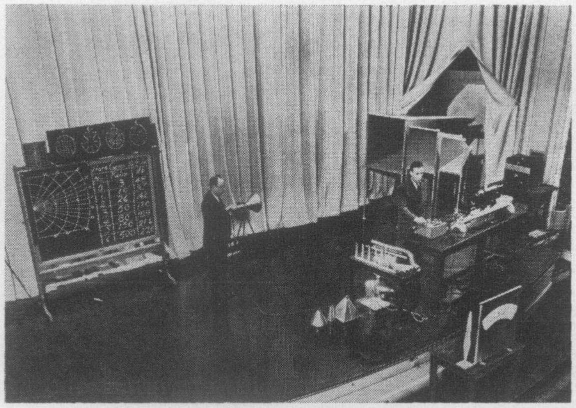

Fig. 6—Second demonstration of waveguides before the IRE on February 1, 1939. This emphasized measuring techniques as well as the electromagnetic horn.

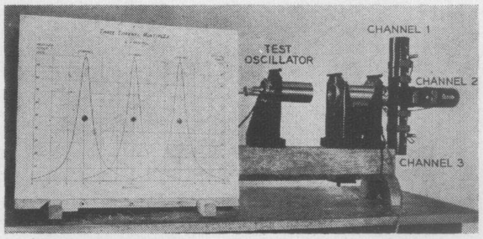

Fig. 7—An early form of three-channel multiplex and its measured frequency characteristic as of 1940.

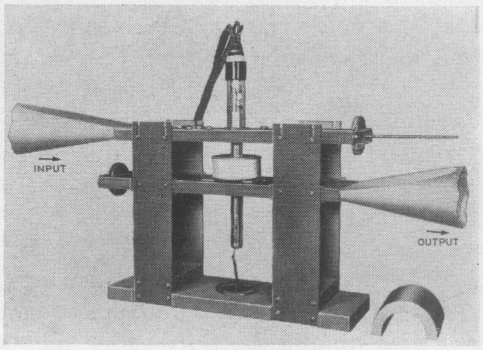

Fig. 8—An early adaptation of the klystron amplifier to waveguide use, 1939.

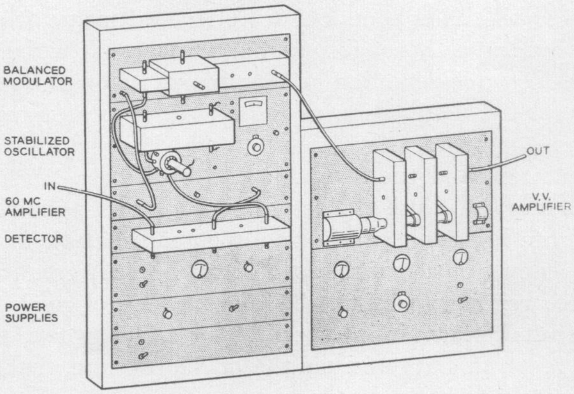

Fig. 9—Microwave apparatus as of the summer of 1941. Sketch from the notes of a project engineer for a proposed 3000-Mc ($\lambda = 10$ cm) microwave repeater for relay use. The apparatus was built, but its assembly and testing was interrupted by war effort.

including such composites as filters, transformers, and waveguide matching devices, but the gathering war clouds over Europe made its presentation appear unwise.

The principle of multiple reflection from discontinuities and the associated principle of cavity resonance played an important part in microwave development. In some cases they were used to match a source of power to a waveguide. In others they served to match the waveguide to a receiver, perhaps a crystal detector. In still others they served to pass freely a band of frequencies, perhaps a television channel, while discriminating sharply against adjacent frequencies. Together these principles formed the foundations of microwave circuitry.

The evolution of microwave circuitry was greatly aided by mathematical theory. The latter showed that the various reflecting discontinuities, such as irises and semiconducting bodies could produce certain impedance effects not unlike those of familiar radio practice. The relationships, however, were rather complicated and in extreme cases involved hyperbolic functions, a subject which many engineers find difficult. Engineering analysis was greatly facilitated by certain graphical analyses devised by Phillip H. Smith.[19] Not only were laborious calculations avoided, but, while the work was in progress, the engineer could visualize the step-by-step processes under way. Indeed, in some cases he could look

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[19] P. H. Smith, "Transmission line calculator," *Electronics*, vol. 12, pp. 29–31; January, 1939. "An improved transmission line calculator," *Electronics*, vol. 17, pp. 130–133, 318, 320, 322, 324–325; January, 1944.

forward to the answer. Few gadgets of microwave circuitry have been more useful than the Smith diagram.

SPECIAL MATERIALS

There developed at an early date a need for special materials. Not only was there a need for metals of good conductivity, for example, silver, but there was a need for special dielectrics and also a need for magnetically permeable materials. The latter were not readily achieved, but ultimately they too appeared. Not always was there a need for low-loss materials, but indeed sometimes the need was for materials with substantial loss. Early forms were resistance films and also absorbing plugs placed in the path of guided waves. As they were made more stable, some became standards of attenuation and others became terminators for microwave transmission systems. Such materials have played a very important part in the development of methods of microwave measurements.[20]

Sometimes the need was for rather unusual materials. One such need was for a material whose resistance varied nonlinearly with amplitude. Such a material already existed in the form of the crystal detector of early radio practice. Starting from these humble beginnings, the crystal detector was greatly improved by Russell Ohl of the Bell Telephone Laboratories and many others, and became a thoroughly stable rectifier. With the advent of double detection in microwaves followed by certain related modulation processes, the crystal detector became an extremely important device, in both the modulation and the demodulation of signals. An even more important use of this principle made it possible to generate harmonics and thereby extend materially the frequency frontier of microwave research. A great deal of research has gone into the improvement of good nonlinear materials. It is especially interesting, too, that this research triggered off the chain reaction that led ultimately to both the transistor and the solar battery, as well as to the important branch of physics known as physics of the solid state.

Another important microwave device of the prewar era was the thermistor. It depends for its success on the properties of certain materials, notably the oxides of manganese, cobalt, nickel, and copper, to change resistance with temperature. A tiny bead made from a mixture of these materials, when matched to a waveguide and heated by received wave power, provides a measure of microwave power. It first came into use in 1936. The wavemeter and the standing-wave detector shown in Fig. 4, together with the stabilized detector, the thermistor, and the standard decibel attenuator provided many of the measurements necessary for the early development of microwaves. Today all remain important elements in microwave measurements.

In the late summer of 1940 a visiting mission from England brought to America their best radar techniques, including the pulsed magnetron, a device giving not only greatly increased power, but an output signal that was well adapted to radar. At the Bell Telephone Laboratories, in particular, the visitors saw the latest in microwave techniques. These later proved of great value in pushing radar to the higher frequencies needed for accurate bombing and for the precise directing of naval gunfire.

WARTIME DEVELOPMENT

The development of microwaves was greatly accelerated in the late summer of 1940 when the National Defense Research Committee was formed, with radar as one of its principal objectives. This organization promptly set up, both at the Massachusetts Institute of Technology and at Columbia University, special laboratories to develop and apply microwave techniques to radar problems. This grew rather rapidly to a huge organization of several thousand top-flight scientists marshalled mainly from universities of the United States and Canada. In addition, very important but less publicized parts were played by other organizations.

Microwave research continued at the Bell Telephone Laboratories, and shortly there followed radar designs for field use, for use in fire control on ships and for use on both submarines and airplanes. Comparable research and design came from the Radiation Laboratory of the Massachusetts Institute of Technology. Composites of the best designs were subsequently manufactured in quantity. Fig. 10, selected largely for its ready availability, is representative of the end results of this work, and is important because it represents early fruition of microwave techniques.

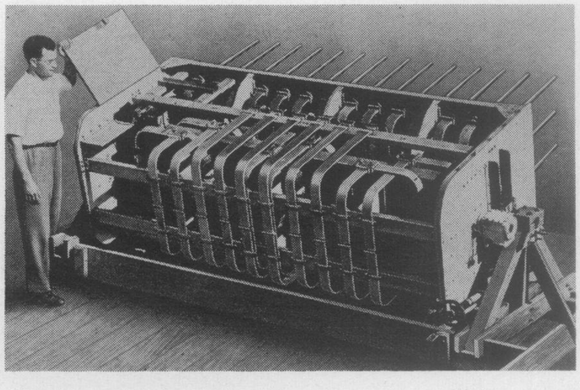

Fig. 10—An early form of microwave radar utilizing waveguide techniques. Not only were microwaves guided to the various antennas, but the phase was varied progressively, thereby causing the beam to scan a distant landscape.

The fundamental building blocks comprising microwave techniques were by no means complete before the War. A great many came during the War and a few followed the War. Because of wartime restrictions and the necessity of close team work, individual credits were often sacrificed. Mention should be made, in particular,

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[20] G. K. Teal, M. D. Rigterink and C. J. Frosch, "Attenuator materials, attenuators and terminations for microwaves," *Trans. AIEE*, vol. 67, pp. 754–757; August, 1948.

of devices by which phase could be added progressively to a waveguide line. This was a product of A. G. Fox of the Bell Telephone Laboratories in 1941.[21]

Also, there were junctions of four waveguides so arranged that when power was introduced in one branch it divided equally between two alternate branches while being balanced at the fourth branch. This had a counterpart in the hybrid balance of ordinary telephone practice. It was proposed by W. A. Tyrrell of the Bell Telephone Laboratories in 1941.[22] Almost as important was a particular form of the balance in which there was an uneven balance between adjacent arms while a balance was maintained at the fourth arm. The latter became known as the directional coupler. Its origin is somewhat obscure because of the many people in war work at the time. However, one early description was given by Mumford in 1947.[23] All of these devices promptly found practical use.

During the War, it was discovered by Robertson and King[24] that falling rain could absorb and scatter large amounts of passing wave power at all frequencies above about 10 kMc. Also it was predicted by Van Vleck and verified by Becker and Autler that there was an absorption band for water vapor (not water droplets) at 22.3 kMc. Other absorption bands were predicted by Van Vleck and verified by Beringer for oxygen at 60 kMc and 120 kMc as well as many others at still higher frequencies. Rain absorption in particular seemed very important for it posed a considerable threat for the future use of the higher frequencies for purely radio uses.

The absorption bands due to water vapor and oxygen came as no surprise, for Professor Williams and Dr. Cleeton[25] of the University of Michigan, several years before, had found that ammonia gas absorbed a narrow band of frequencies centering around 45,000 Mc. This was the forerunner of some very fruitful molecular and atomic research in which the microwave techniques were to play a very important role.

It was in this period of microwave research, too, that it was discovered that measurable amounts of microwave radiation could be received from the sun.[26] This discovery, together with Jansky's discovery of noise from interstellar space, ushered in modern radio astronomy. Although initiated in America, this work was quickly endorsed in both Australia and England, and impressive research programs were set up promptly. Radio astronomy now represents one of the more important areas of fundamental investigation, with budgets amounting to millions. It is the proud accomplishment of microwaves development that it should be able to aid in the exploration of both the infinities of outer space and the infinitesimal interior of the atom.

In this wartime period microwaves virtually leapfrogged their way across the frequency spectrum from 3 kMc to possibly 30 kMc, all in a period of two or three years. In each case new sources of power were needed to make a new beachhead while the needed measuring apparatus was being developed, preliminary to the evolution of new electronic devices. To break an apparent stalemate and supply, when needed, adequate research tools, the expedient was used of generating, by means of crystals, the harmonics of such frequencies as were readily available. Steps from 3 kMc to 9 kMc to 27 kMc were typical. Good measuring equipment including wavemeters, standing-wave detectors, power-measuring devices, and standard attenuators were built for all of these ranges prior to 1943. Today harmonic production remains one of the favored methods of exploring the frequency frontier. Microwave measurements were naturally an essential part of microwave research.

MICROWAVES IN THE POST-WAR PERIOD

Although the number of fundamentally new principles of the microwave techniques diminished after the War, the number of applications increased markedly. Released from urgent wartime responsibilities, engineers turned naturally to peacetime uses. Communication, as contrasted with radar, was perhaps the most obvious alternative. Research had already evolved various microwave sources and also before the War had come an amplifier for such signals. The postwar period was to see a marked extension of its frequency range. The klystron, the first practicable electronic device to break from conventional principles, was a most welcomed prewar entrant to the microwave field. Soon came the closely-spaced triode, an ingenious adaptation of the space-charge principle to the new microwave task. Shortly, there came the traveling-wave amplifier, a device that could amplify extremely wide bands of frequencies. All three devices could assume the form of oscillators as well as amplifiers, thereby providing sources of microwave power at ever increasing frequencies. Details of the development of electronic devices are covered in other articles of this issue. These have been important in the history of microwaves, for they have paved the way to wider use.

Microwaves were aided tremendously in the postwar period by the development of new materials. Of particular importance, were the ferrites, insulating materials that exhibited pronounced magnetic properties. Particular ferrites were able to produce, in the microwave range, the effect of Faraday rotation so familiar in optics. One result of this development was a new family of microwave circuit components, each capable of a

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[21] A. G. Fox, "An adjustable waveguide phase changer," PROC. IRE, vol. 35, pp. 1489–1498; December, 1947.

[22] W. A. Tyrrell, "Hybrid circuits for microwaves," PROC. IRE, vol. 35, pp. 1294–1306; November, 1947.

[23] W. W. Mumford, "Directional couplers," PROC. IRE, vol. 35, pp. 160–165; February, 1947.

[24] S. D. Robertson and A. P. King, "Effect of rain upon the propagation of waves in the 1- and 3-centimeter regions," PROC. IRE, vol. 34, pp. 178–180; April, 1946.

[25] C. E. Cleeton and N. H. Williams, "Electromagnetic waves of 1.1 cm wave-length and the absorption spectrum of ammonia," *Phys. Rev.*, vol. 45, pp. 234–237; February, 1934.

[26] G. C. Southworth, "Microwave radiation from the sun," *J. Franklin Inst.*, vol. 239, pp. 285–297; April, 1945.

variety of useful functions. In one particular case, a ferrite device passed microwave power freely in one direction, while discriminating sharply against power in the reverse direction. All of this may be accomplished without the loss of one half of the transmitted power that is inherent in most wave-balancing systems. (This material is described more completely in other articles of this issue.)

Other devices playing an increasingly important part in microwaves resulted from the further study of the general subject of solid-state physics, which has already led to such important devices as tunnel diodes, parametric amplifiers, masers, and to low-noise receivers, generally. The latter are particularly useful in radio astronomy and also offer promise of being useful in the intercontinental communications by way of reflecting satellites. It is too early to properly evaluate the importance of such devices, but it is quite obvious that they will be very important.

SOME POSTWAR RESEARCH AND APPLICATION

While the development of microwave radar has continued unabated for both military and peacetime uses, many other applications have appeared. In particular, microwaves have become very useful in the radio relaying cross-country of broadbands of visual, audio, and telegraph signals. Continuing a program started in 1941 but interrupted by the War, the Bell System resumed the task in 1943 and in 1947 set up a thoroughly practicable radio relay system between Boston and New York on a frequency centering of about 4 kMc. Repeater stations located at intervals of perhaps thirty miles picked up attenuated signals, demodulated them to a relatively low frequency, and after remodulation and amplification transmitted them onward at a slightly different frequency. The system often referred to as TD-2 was soon extended from New York to Chicago and ultimately to the Coast. It is now a vast network estimated in 1960 at 40,000 route miles comprising nearly 40 per cent of the total Bell System intercity circuit mileage. In the meantime similar systems have been developed by others in America and elsewhere. In particular, considerable use of microwave radio relay is also being made by the U. S. Government, the Western Union Telegraph Company and the various pipe-line companies and Turnpike Commissions. The combined use of such systems is estimated (1960) at 32,000 route miles.

Improvements in microwave relay systems have made it possible, by using frequencies as high as 6 kMc, to transmit over the same system alternatively either 10,800 telephone channels or perhaps a half dozen television channels. This newer application is sometimes referred to in Bell System circles as the TH system.

In 1960 experiments were started looking toward microwave communications over transoceanic distances, through the intermediary of a reflecting balloon orbiting at perhaps 1000 miles above the surface of the earth. Satellite periods of two hours were typical. Though the useful period of a single orbiting reflector is, according to this plan, definitely limited to a few minutes for each transit, it is expected that several such reflectors will provide practically continuous service. Frequencies of the order of 7 kMc are contemplated. Although the research leading to this rather unusual relay system, has, for the most part, made use of conventional methods, there are notable exceptions. Like the receivers of radio astronomy which look toward the low temperatures of interstellar space, these receivers may also profitably use low-noise detectors. This has entailed an interesting bit of solid-state research on the fringe of microwave research.

Much of the early research with microwaves centered around the so-called dominant or TE_{11} mode, from which have flowed most of our present-day microwave applications, both in radio and radar. The dominant mode is but one of the double infinity of modes or configurations that are possible in a waveguide. There is another mode of great practical interest, particularly in cases where it is desirable to guide microwaves to great distances. In this mode, which is known as TE_{01}^{0}, the lines of electric force are everywhere coaxial circles, parallel to the walls of the circular conducting pipe and for this case the attenuation, since it involves only tangential currents, progressively decreases as the frequency is indefinitely increased. During the thirty years since this principle was first understood, there has been the constant hope that a microwave transmission line might sometime be evolved that would incorporate bandwidth with relatively low attenuation.

After years of painstaking research, the practical realization of this objective now seems assured. Attenuation of the order of 2.5 db per mile is typical with bands corresponding to perhaps 200,000 speech channels. This assumes pipes to be perhaps 2 in. in diameter. Thus future communications seem to be leading not only toward radio but toward a form of the time-honored wire line. Only time can tell how the work-load will be divided between the two media. It is likely that both will be used. Radio will probably be preferred both for the mobile services and for radar. But guided transmission will probably be preferred in cases where either privacy or freedom from interference is paramount.