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CURRENT PROBLEMS IN RESEARCH

Microwaves

They have important uses in defense projects, industrial developments, and basic physical research.

E. L. Ginzton

Although the term *microwave* is often encountered in the technical and scientific literature, it may be well to begin this review by restating the meaning of this term as it is known to the workers in the field. It is convenient to think of the electromagnetic spectrum as being divided into two parts which differ from each other in the methods available for the generation and detection of radiation. The first of these regions, that of shorter wavelength, is characterized by the fact that both generation and detection of radiation involve quantum effects (such as the radiation of light from an atom arising from the transition of electrons from one energy state to another). In this region can be listed cosmic radiation, visible light, infrared, and so on. The second part of the electromagnetic region, called the radio region, is characterized by the fact that electromagnetic energy can be generated by the circulation of electrical currents through conductors and, in contrast to the first case, the frequency of radiation can be controlled by selecting the size and configuration of electrical circuit elements. It is the extreme high-frequency end of the radio spectrum which is called the "microwave region," and these radio waves are called, for brevity, "microwaves." This qualitative definition of microwaves indicates that a clear distinction cannot be made between microwaves and short radio waves on the one hand, and microwaves and infrared radiation on the other.

At the present time, for various reasons which will be considered, it has not been possible in any practical way to generate radiation having a wavelength shorter than a few millimeters. The long-wave end of the microwave region is also vague, and microwave devices and techniques are occasionally used at frequencies which are attainable by refinement of ordinary radio devices and practice. Thus microwave principles and techniques are sometimes found useful at wavelengths as long as 100 centimeters. Expressed in units of frequency, the microwave region can be said to extend from about 300 megacycles to about 150,000 or 200,000 megacycles. This is a very large frequency domain, which provides room for many classes of radio service which find themselves crowded in the ordinary radio region which, by comparison, covers only a few hundred megacycles.

In considering the objectives of research in this field, it is important to observe that, in contrast to many branches of science, there is no intrinsic interest in conducting research in this field in itself. Whereas, for example, one can study cosmic particles in the hope that this study will shed new light on the basic properties and laws of nature, the study of microwaves in the same sense is pointless. The study of electromagnetic phenomena in the visible and radio regions during the last century has firmly established fundamental principles, and these, of course, govern the behavior of microwaves as well, even though the generation and observation of microwave phenomena did not become really practical until quite recently.

This does not imply, of course, that research which makes *use* of microwave techniques is not possible or profitable—quite to the contrary. The availability of electromagnetic radiation in the microwave region has opened up broad new areas of research in many fields. The significance of microwave research can perhaps be best understood by briefly describing some of the major fields of activity made possible by the development of methods of generation, detection, and measurement of microwave radiation. This will be attempted in the section on "Current applications" below.

It is important, then, to observe that research in the microwave field is clearly governed by the possible applications to which a particular discovery or development might lead. In other words, research in the microwave field must, of necessity, be *applied research,* always directed toward a useful goal in some other field. The fact that microwave research is of applied nature does not mean that the work is either mundane or of limited interest. Both the nature and methods of research are often most challenging, and it is gratifying that the results of the work frequently find application as both tools of fundamental research and in more conspicuous practical applications. Examples of the former are the use of microwaves in spectroscopy, in radio astronomy, and in particle accelerators; and of the latter, their use in radar, television relays, communications, navigation, cancer therapy, food sterilization, and home cooking ranges.

Since microwaves are radio waves, it is not surprising that the problems encountered in the field are those well-known in radio technology. These are: methods of generation and amplification of radiation; reception, detection, and amplification of incoming signals; and methods of measurement of the electrical quantities which are needed to describe accurately the behavior of electromagnetic waves in an experiment or system. Just as often happens in the ordinary radio region, many of the new

The author is director of the Microwave Laboratory, W. W. Hansen Laboratories of Physics, Stanford University, Stanford, Calif.

microwave problems arise because it becomes of interest or importance to try to work at frequencies which have not been successfully used before; or to generate a greater amount of power than has been heretofore possible; or to try to find methods of amplification which would permit the detection of weaker signals, more closely approaching the theoretical limits imposed upon a given system by its temperature. All of these are practical problems, but their solution may permit, for example, a better understanding of molecular structure, or a novel astronomical observation.

In addition to describing the various applications of microwaves for the purpose of general interest, this article will be concerned with discussion of some of the problems that are encountered in finding means to generate, detect, and amplify power in a manner dictated by those applications which are now known to the workers in the microwave field. A more complete discussion of the principal areas of application of microwaves would be beyond the scope of this article.

Origin

There are four general reasons for the original and continuing interest in the microwave region. First, the development of successful methods of generation and detection of microwaves has made possible the investigation of certain classes of physical and chemical phenomena; microwave molecular spectroscopy is an example of one technique which is used in this work. Second, the wavelength of microwaves is so short that it is quite practical to build transmitting and receiving antennas which are large compared with the wavelength; thus, many principles of physical optics can be made to apply, and as a consequence, it is possible to focus and direct microwave radiation in a manner similar to that of light. Third, the wavelength of microwaves is still sufficiently long so that these waves, like ordinary radio waves, are not scattered and stopped by rain, fog, or clouds. Fourth, as mentioned before, the region between the shortest and the longest end of the microwave region is extremely wide in terms of frequency. Until the advent of microwave devices, all types of radio service had to be contained within a region of a few hundred megacycles. Consequently, the development of radar systems and of equipment for aircraft navigational and blind-landing aids and the expansion of communications of all types became feasible only after the microwave region of the spectrum became usable. The microwave region extended the frequency range available by a factor of approximately a thousand and will probably provide sufficient room for most of the foreseeable demands for many years.

It is difficult to present an accurate historical account of research in the microwave field because it developed slowly at first and extremely rapidly in the recent past. It is of interest to note that the first experimental verification of Maxwell's theories was carried out by Heinrich Hertz in 1888, and that this work was in the microwave region. In a series of now-famous experiments, Hertz demonstrated the feasibility of radio propagation and the identity of Maxwellian radiation and ordinary light by showing that, like light, "microwaves" obeyed the known optical laws of reflection, refraction, and polarization. These experiments were repeated by others, and, after a rapid improvement in technology, the first radio communication was established. In the course of the original development the primary interest centered on the problem of communication over long distances and, hence, the need for comparatively high power. This could then be obtained only at longer wavelengths, and the original "microwaves" were all but forgotten. Serious interest in the possible use of very-short-wavelength radiation did not begin until the mid-1930's, when it became increasingly evident that methods of rapid, precise detection of aircraft through fog, clouds, and darkness would be of great military value.

Development

From the time of the early workers in the field—Hertz, Lodge, Muirhead, Popoff, Braun, Tesla, Marconi, and others —to the beginning of the intense development work in the late 1930's, many significant contributions had been made by scientists throughout the world. The experiments of Hull with the split-anode magnetron in the early 1920's and the further development of this device by workers in Japan, made it possible to generate small but significant amounts of microwave power. In the early 1930's, work began on molecular spectroscopy, and this and related research led to further improvement in methods of generation, detection, and measurement.

Theoretical studies in the 1930's were also of major importance. Southworth and his collaborators at the Bell Telephone Laboratories, and Barrow at Massachusetts Institute of Technology, discovered the principles of guided propagation which eventually led to the widespread use of hollow pipes as a means of conducting electromagnetic energy from one place to another, instead of the wires which had been used before. The development of these transmission-line concepts was fundamental, since they made possible a system for transmission of high-frequency power without appreciable loss (which would otherwise be expected), and also because they provided an understanding of the behavior of electromagnetic waves in bounded regions. Another important contribution during this period was due to Hansen at Stanford University, who showed that empty or dielectric-filled containers could act as resonant circuits, just as the coil and condenser do at the lower radio frequencies.

In the middle 1930's the generation of microwave power in the amounts required for practical applications was difficult for two principal reasons. In all power-generating devices which use electrons it was considered necessary that the flight-time of the electrons across a given electron tube be small compared with the period of a single cycle of the radio-frequency wave. This was thought to be a fundamental limitation on the generation of high-frequency power since, if the time of flight were a full cycle, any work done by the electrons on the circuit during the first half-cycle would be cancelled by the work done by the circuit on the electrons during the second half-cycle. Electron tubes were designed, then, so that the flight time was negligible compared with a cycle, and this in turn meant that it was necessary to make the tubes smaller and smaller as the intended frequency increased. Because of this limitation, and the necessity of using low-efficiency coil-and-condenser circuits, it appeared that it would be impossible to generate any substantial amount of power at microwave frequencies—not enough, in any case, to be useful for most practical applications.

The fundamental "transit-time" limitation mentioned above was eventually circumvented by a new method of obtaining radio-frequency power in electron tubes. The new development was the result of the discovery of the so-called "velocity modulation" of electron streams, which was due to Heil and Heil in Germany, the Varian brothers at Stanford University, and Hand and Metcalf at

General Electric. Instead of attempting to make the electron flight-time inside the vacuum tube small, the principle of velocity modulation made intentional use of transit times which were very large. To convert a homogeneous electron stream into a pulsating one which could deliver power to a high-frequency circuit, the electrons were made to *bunch* along their path because of the difference in their speeds.

The combination of the principle of velocity modulation of electron beams and the "cavity" resonators of Hansen led to the important development, in 1937–39, of the "klystron" tube, which proved capable of performing, at microwave frequencies, many of the tasks expected of the conventional vacuum tube at lower radio frequencies.

The beginning of World War II accelerated the development of the microwave field by demanding greater power, better detection systems, and a more complete understanding of the various problems associated with the use of microwave methods for radar and communication. Important discoveries in England led to rapid development of the magnetron and eventually permitted this device to deliver a peak power of several million watts at wavelengths in the neighborhood of 10 centimeters.

It is not appropriate to attempt a complete description of the many significant accomplishments in microwave technology during the war. However, it may be of interest to note that the work of the Radiation Laboratory of Massachusetts Institute of Technology eventually led to the publication of a 20-volume series which dealt with the theory and application of microwaves to the radar problem. Because of the importance of the problem, the state of the microwave art advanced a remarkable distance in a short period of five years. Not only were many complicated and successful systems developed, but theoretical understanding of almost all aspects of the field also reached a point of near perfection. The practical devices which emerged from this work were far advanced in nearly every major respect. For example, more peak power could now be obtained at microwave frequencies than had been obtained at the lower radio frequencies; radio receivers could distinguish signals which were only ten times as large as the noise due to natural causes (thermal agitation) in the circuits themselves; theory and design of antennas were highly developed; measurement techniques were perfected to the point where all of the usual electrical quantities could be measured nearly as well as they could be in the radio region, which had been under study for the preceding 50 years; the theory of the behavior of electromagnetic waves in closed regions was highly developed, and the transmission theory could be considered virtually a closed topic except for details of design.

As a result of these war-time developments, it was clearly evident that the future of the microwave field held great promise. Many of the expectations of this period have been fulfilled in postwar developments. Some of the more important of these are described below.

Current Applications

Communications and defense. Perhaps one of the simplest and most direct consequences of the war-time developments is the use of radar for maritime purposes. Today every large ship carries one or more radar sets for the purpose of navigation in bad weather. Although present maritime rules prohibit navigation solely by radar, its use contributes in large measure to the prevention of serious maritime accidents. Maritime radars are designed to indicate the presence of ships, land masses, icebergs, and other objects at distances as far as the horizon. Other types of radar are designed to locate accurately objects close by, and this information is useful in navigation through narrow channels, in harbors, rivers, and in the Great Lakes.

Radar is equally useful in the navigation of aircraft. Although an ideal navigational system has not yet been developed, radars of several types are in constant operation at every major commercial airport; these are used to establish safe traffic patterns by stacking and controlling the aircraft and are also used to assist in landing the aircraft in bad weather. Some modern aircraft also carry airborne radar which permits them to detect adverse weather conditions which are not suitable for convenient or safe flight.

One of the principal present uses of microwaves is in providing a means of communication where a broad frequency bandwidth, on the order of several megacycles, is required. This bandwidth is necessary for rapid transmission of signals which contain a large amount of information, television being an important example. In the United States today, every major city can now receive television programs which originate anywhere else in the United States. This is accomplished by transmitting microwave power over short distances, say 20 miles, and repeating the transmission to cover longer distances. Many countries in Europe and elsewhere have similar networks of "repeater" transmitters either in operation or in development. Some of these countries are also developing similar relay networks to augment or replace the older wire systems of telephone communication. In many parts of the world, microwave methods provide the only practical form of communication. In addition, the recently developed form of microwave relay communication which uses the method of scatter-reflection from the atmosphere makes possible relatively long-distance communication; and this provides means of communication in those sections of the world where closely spaced relay links are either impractical or unnecessary.

The applications of microwaves in defense systems are both numerous and important. Microwave applications are found in nearly every branch of the military service and are used for radar, communication, and navigation, and for the launching, guidance, and fusing of missiles. Some of the defense projects which use microwave techniques have reached very large proportions as, for example, the DEW radar line being built jointly by Canada and the United States.

Science and industry. Just as spectroscopy studies of the emission and absorption of visible radiation have led to an understanding of atomic structure, microwave spectroscopy studies have brought about a more complete understanding of molecular structure. A number of potential applications of great importance have come from this work. An example of these is the development of the "atomic clocks." In one of these atomic clocks, use is made of the spectral line associated with the characteristic inversion frequency of an ammonia molecule. This line, located conveniently at 23,870 megacycles, is extremely stable and is therefore useful as a frequency standard. This spectral line can be observed either by finding the center of the absorption band or, alternatively, by the recent discovery of "induced emission" in a device called the "maser," which will be described in greater detail later. By using one of these methods, it is possible to construct a device which will produce microwave signals whose frequency can be made considerably more stable than the frequency of any other man-made source. By reducing the frequency by conventional electronic methods to the neighborhood of 1000 cycles, it is possible to use this frequency to operate an ordinary clock. The time derived from an atomic clock by such methods promises to provide a new standard of time, which will be independent of the fluctuations which are known to occur in the present standard, the rotational frequency of the earth. If atomic clocks can be made to attain the precision which present experience indicates is possible, many important discoveries and practical developments should result. In the field of science, for example, it should be possible to repeat the famous but inconclusive experiment of Michelson and Morley to more accurately ascertain whether ether drift does not, in fact, exist. Another application is the possibility of devising completely laboratory-contained experiments to test the theory of relativity.

One of the possible practical applications of extremely stable frequency sources is that of devising new types of navigational systems for use in the air and at sea, and possibly—should the need arise—in the space beyond the earth. If a radio transmitter and receiver, with oscillators operating at precisely the same frequency, are located, respectively, at a fixed station and on a moving vehicle, then the motion of the vehicle will result in the received signal being Doppler-shifted. By comparing the received signal with one generated in the vehicle, the velocity of the vehicle can be determined simply by measuring the frequency difference; and the vehicle's position can be found by integration of the Doppler frequency—that is, by counting the cycles of the frequency difference during the time elapsed. Stability of an oscillator on the order of one part in 10^{10} should result in the determination of vehicle velocity to an accuracy of 1/20 mile an hour. Such stability in atomic clocks does not seem impossible, and is in fact already being approached by some of the devices now being tested.

The ammonia maser can also be used as an amplifier of weak signals. Since it does not use charged electric particles in the process of amplification, the usual noise-generating mechanism in receiver circuits is not present, and this, in principle, makes it feasible to build "perfect receivers"—that is, receivers which can identify electrical signals which are just slightly larger than the natural noise existing in space. This goal has been the object of extensive research at all radio frequencies, including the microwave region; however, at microwave frequencies the known methods of detection and amplification have always resulted in the introduction of noise by the detector or the amplifier to the extent that it has been impossible to detect signals which were weaker than approximately ten times that of the natural noise. It has already been demonstrated that the ammonia maser can bring about a significant improvement in the quality of microwave receivers, and these discoveries have stimulated reseach along related lines.

Another application of microwave power is its use in accelerating particles to very high energies. High-energy electrons, for example, are useful for many purposes: in the range of a few million volts, they may be used for sterilization of food, drugs, and other products and for inducing chemical reactions not otherwise easily produced; in the energy region from a few to 20 or 30 million volts, they are useful for generation of x-rays for industrial radiography and for cancer therapy; in the energy region above this, extending into the multi-billion-volt range, electrons are useful as an important tool of nuclear research. In each one of these applications, microwave methods of accelerating particles are convenient and practical, and in some cases represent the only known method of attaining the desired result. The state of contemporary microwave practice is sufficiently advanced in these fields so that no fundamentally new research is required. What is necessary, of course, is the investment of large sums of money for development and construction of appropriate machines.

Still other applications of microwave radiation may be mentioned. Radio-frequency heating has been a standard technique available to industry, and it is not surprising that microwave power should also find application for this purpose as well. Generally speaking, the methods of generating microwave power are not as efficient as those used to generate the lower radio frequencies. Therefore, microwaves are used for heating purposes only when there is some specific advantage to be gained at shorter wavelengths. A few of the applications in which this is the case are the following. Molding of certain plastic materials can be conveniently carried out by introducing microwave power into the molding-machine cylinders just prior to extrusion. Also, powdered plastic material which is contained in a metallic cylinder can be made to be a resonant microwave circuit and will therefore absorb microwave power readily and rapidly. This process lends itself to mass production of plastic products. A third application, based on the same principle, is the microwave kitchen range. In this application, many kinds of food, by virtue of their dielectric properties, can be heated almost instantaneously.

Current Problems

As has been noted above, microwave research is oriented toward applications in other fields of science and toward industrial applications, and it has led to many important advances. We now turn our attention to some of the central problems which presently concern workers in the field, and also consider further possible applications which might arise. It should be noted here that the following observations do not include activities which are basically a refinement or an extension of known principles, although such work is, of course, very important; it would not be possible to provide a comprehensive description of even the most significant of these activities. The problems considered below are arbitrarily confined to those which involve the search for new principles, new methods, and new applications.

The following general areas of the microwave field are now receiving or can usefully receive attention as topics of research. The general topics listed, and some current approaches to these, are described below in greater detail.

Extension to higher frequencies. In the mid-1930's it was important to find practical means of generating microwave power; one of the central problems at the present time is to find methods of generating radiation in the frequency region beyond that now usable—in the millimeter and submillimeter range. As with the earlier work, there are specific and general reasons for this interest. Among the specific reasons are those which concern the use of short wavelengths in the field of molecular spectroscopy, and also the further extension of the usable frequency spectrum for the continuously growing needs of the communication industry. The general reason, which is the one that fundamentally motivates all new microwave research, is that no one can now predict (just as no one could have predicted the multifarious applications of radio and microwaves) what future applications and discoveries the availability of this broad new spectrum will lead to. It is of very great interest to find methods of generating radio-frequency power in the region between radio waves, on the one hand, meters. For other types of microwave generators, such as the magnetron and the traveling-wave tube, the differences in the final result are surprisingly small, in spite of the substantial difference in the method of operation and the configuration of the various devices.

As a result, it has been clear for some time that higher frequencies cannot be attained by application of presently known electronic principles. Several systematic searches for other possibilities have not yet revealed any plausible approach to the problem. The workers in the field have therefore a new challenge: to find a solution to a seemingly hopeless problem. The situation today in this field is similar to that in the mid-1930's, when methods of microwave generation were unknown. The present picture is not completely pessimistic; some suggestions are being explored along lines which will be described in a later part of this article.

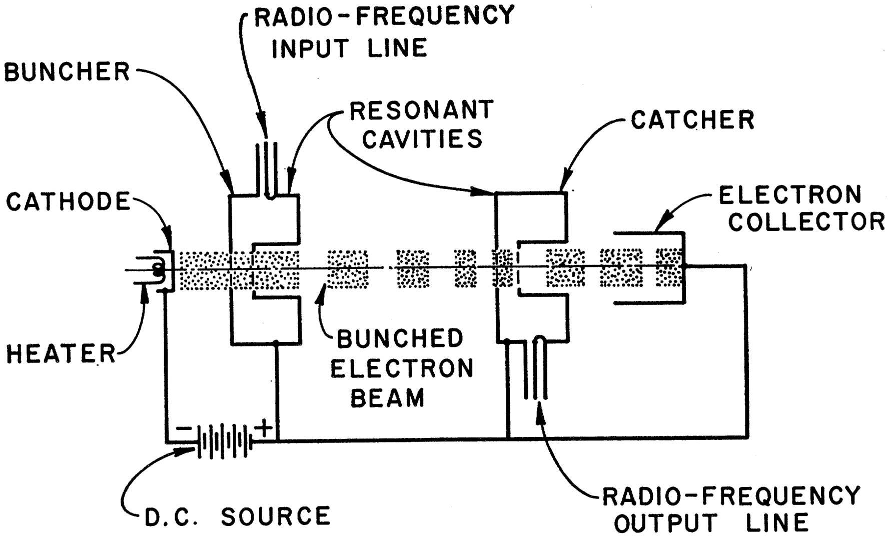

Fig. 1. Essentials of a klystron tube. Electrons emitted from a cathode are accelerated and focused into an "electron beam." The electrons, in passing through the "buncher" cavity, experience time-varying forces due to the radio-frequency fields there. The resultant motion of electrons creates bunches of electrons, approximately as shown. These create pulsating forces in the "catcher" resonator and thus induce amplified signals which can be removed by a coupled output transmission line.

and infrared radiation on the other. An immediate objective of research in this field is to find new methods which will increase the available spectrum by another factor of ten, reaching perhaps down to a wavelength of 0.1 millimeter.

These objectives cannot be reached by simple extension of present electronic methods of generating radio-frequency signals. All present known electronic devices have a fundamental high-frequency limit above which they cannot be made to work. The details of these limitations are complicated, but some insight into the main reasons can be quite readily attained. As the wavelength at which one is interested in building a microwave generator is made shorter, the physical size of the device is necessarily made smaller in proportion. All microwave devices require the use of cavities or circuits whose dimensions are related to the operating wavelength. It also happens that in all electronic devices there is a critical amount of electronic current which must be made available in order to permit operation. If the available current is less than this critical amount, operation of the device becomes impossible, because the power that can be generated by this current is not sufficient to supply the heating losses in the circuits of the device. But as the wavelength of the device is made smaller, the region through which the electron current must pass is also made smaller. This means that the higher the frequency, the lower is the available current, and this is further complicated by the fact that, in general, the required current becomes higher. This situation can be made clearer by considering a specific situation—for example, a klystron, the simplest of all microwave devices. Figure 1 is a schematic diagram of a klystron, in which an electron beam is produced by accelerating electrons from a cathode and focusing them into a cylindrical beam. Along this beam there are a number of resonant cavities, the first of which permits variation of the electron velocity, due to the radio-frequency voltage across its opposite poles. Subsequently, because of the velocity variation, the electrons group themselves in bunches and are able to impart their kinetic energy to the potential energy of the last resonator. The exact process of generation of microwave power is not important for this discussion, but it is important to note three things: (i) As the wavelength is made shorter, all of the dimensions in Fig. 1 need to be reduced in proportion to the wavelength; (ii) as a result, the amount of current available from the cathode is reduced in proportion to the area of the cathode—that is, is reduced as the square of the wavelength; (iii) the losses in the conductors of the resonant cavities become higher. Thus, as the wavelength is made shorter, the available current is smaller, although the required current is greater. At some specific wavelength, therefore, a device of this sort will cease to work. A more careful analysis of this problem demonstrates that a klystron cannot be made to work at wavelengths appreciably shorter than a few millimeters.

Generation of higher power. For several possible applications it would be desirable to provide even greater power than has been attainable before. Either higher peak power, or higher average power, or both, are of interest. The question of increasing the average power is important, for example, in applications involving industrial heating, television and radio transmitters, and so on. In other applications, such as radar and particle accelerators, it is often of interest to be able to generate higher peak power.

In addition to the question of the power level, another requirement of primary importance in many transmitting systems is the ability of the transmitter to respond to large frequency bandwidth —that is, the range of frequencies which a transmitter is capable of amplifying simultaneously. Questions of this type are especially important in radar applications, and the search for methods of amplifying large bandwidths at high power levels represents one of the most important problems in this field.

Detection and amplification of weak signals. Detection and amplification of weak signals is clearly as important as generation and transmission of higher power. At the present time the principal effort to improve the ability of microwave receivers to respond to weak signals has been devoted to studies of traveling-wave tubes, although the results of this work are applicable to other microwave devices as well. However, because the traveling-wave tube, in common with all electronic devices, uses charged particles, the noise generated in the tube by the electron stream is not negligible, despite efforts to minimize such noise. When the present performance in this field is compared with radio standards, traveling-wave tube operation seems nearly as good as one can expect. But the recent invention of the maser has shown that amplification can be obtained without the use of charged particles. This has led to new possibilities for reduction of noise in detecting and amplifying systems, and these will, without question, be of great importance in the future.

Other applications. The general areas of interest for further research have been stated in terms of microwave applications which are either known today or are possible if certain specific microwave objectives can be attained. It is probable, of course, that still other applications of microwaves will be found. The search for new ideas, new applications, and new methods will continue to be as important as it has been in the past.

There are two areas which seem to provide exceptionally great opportunities for research at the present time. One of these concerns the extension of principles introduced by the invention of the maser: the applications arising from microwave signals which are obtained from systems that do not use electron beams. The second area of speculative interest is the study of possible applications of plasma phenomena in microwave systems—that is, gaseous media in which all or nearly all atoms are ionized. Nearly all radio-frequency generating devices employ electrons exclusively; in retrospect, this seems like an artificial restriction upon the potentialities of electronic devices. That plasma applications have received only limited attention, to date, is due to the fact that plasma phenomena are extremely complicated. The possible importance of this subject, however, is great.

Generation of High Frequencies

Despite many technical difficulties, electronic devices of more or less conventional design have been developed to permit practical application of microwaves at wavelengths as short as two or three millimeters. Outstanding examples of this work are the miniature magnetrons developed at Columbia University and the backward-wave traveling-wave tubes developed at the Bell Telephone Laboratories. Beyond these wavelengths, due to the fundamental limitations mentioned above, the conventional methods do not appear to be useful, even if the fabrication difficulties associated with small size could be resolved. Although as yet there are no obvious means for overcoming this limitation, there are several approaches to the problem now being pursued. It is too early to judge their possible success, but a description may serve as a good example of the work being done in this field.

In one approach, an attempt is being made to obtain microwave radiation from high-energy ("relativistic") electrons by subjecting them to periodic forces. Experiments which use relativistic electrons are currently being conducted by Motz at Oxford University, Coleman at the University of Illinois, and Mallory at Stanford University.

For the sake of illustration, consider an example of one such device, the "undulator" described by Motz and shown in Fig. 2. The electrons are emitted from a cathode (not shown in the illustration) and are accelerated to a velocity closely approaching that of light; this can be readily accomplished by the use of a microwave linear electron accelerator, the understanding of which is again not essential for the present purpose. In the undulator shown, the electrons are made to pass between the poles of the magnets, which are arranged as indicated in Fig. 2. The presence of the periodically spaced magnets causes the electrons to be deflected transversely and to undulate through the system. To understand the operation of this device, suppose an observer is located at some point along the axis of the electrons, as indicated in the illustration. An observer in this position, looking at the electrons head-on, would "observe" that the electrons are vibrating as if they were a current in a dipole antenna; he would, therefore, expect that the undulating electrons would radiate at a frequency which would be equal to the vibrational or undulational frequency of electrons. This frequency, he might think, is equal to the spacing of the magnets divided by the velocity of the electrons, which is approximately that of light. However, this expectation must be corrected because of two factors. Since the electrons are traveling virtually at the speed of light, relativistic effects must be taken into account, and this can be done by assuming that the spacing between the magnets is reduced. Thus, the electrons radiate at a frequency higher than would be expected if relativistic effects were neglected. Further, the electrons are moving toward the observer, and therefore the radiation from the electrons is Doppler-shifted. These two effects, taken together, result in radiation from the electrons (accelerated to a few million volts and with magnet spacing of a few centimeters) in the millimeter and submillimeter range. Experiments of this sort were first done by Motz, who used the linear electron accelerators available at Stanford University; these experiments have in fact shown that the principle can be used to produce electromagnetic radiation which completely bridges the gap between the radio region and the region of visible light.

The principal question that arises in examining the performance of the undulator is that of what intensity can be expected from it. Analysis shows that the behavior of the undulator is very strongly affected by the manner in which the electrons are injected. If the electrons can be sufficiently "bunched" by the linear accelerator prior to injection, so that the longitudinal length of a given bunch is approximately equal to the wavelength which one is interested in generating, the radiation process can become quite efficient. This is due to the fact that all the electrons in the bunch would radiate "together"—that is, radiation from each electron would reinforce radiation from the others. The practical problem is, therefore, to cause the electrons to bunch very tightly; this happens

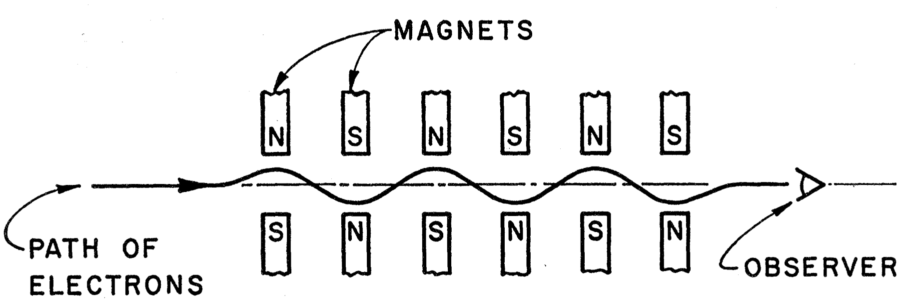

Fig. 2. Elements of the Motz undulator. Electrons arrive in bunches from the left, from a linear electron accelerator, and are forced to execute periodic vibrations due to the forces exerted by the magnets. The observer (with the aid of suitable detectors) at the right will find electromagnetic radiation of a higher frequency than the microwave frequency in the linear accelerator.

to be a difficult problem and is the central one of current research.

The undulator is not the only means for extracting power from the tightly bunched stream of relativistic electrons. Mallory, at Stanford, has observed that injection of a bunched electron stream into a hollow metallic tube produces radiation in the submillimeter range without the employment of any transverse undulation. This phenomenon, which is believed to be due to the extraction of higher harmonics from the bunched beam, seems to be related to the behavior of ordinary nonrelativistic frequency-multipliers. The success of devices other than the undulator also depends upon the initial degree of bunching which can be obtained.

The use of relativistic electrons cannot lead to development of simple, small, inexpensive sources of laboratory power, since this requires a powerful microwave source and a means for accelerating electrons into the relativistic region. Even so, the successful development of these devices would stimulate further experimentation and development and should eventually result in new approaches to the problem.

A different approach is currently being pursued by Linhart of the Comité Européen de Recherche Nucléaire (CERN) in Geneva. Linhart intends to use plasma phenomena in a novel way. His idea can be understood by considering a mechanical analog, as shown in Fig. 3. A weight is suspended by a string which passes over a support, and this can be adjusted to shorten the length of the pendulum or "oscillator." It is well known that the work done by the force F will cause the swinging pendulum to oscillate at an increased frequency, as the string is shortened, provided that the fractional decrease in the length of the string is small during a single cycle of oscillation. According to a well-known theorem, if this "adiabatic" criterion is obeyed, the internal energy of the oscillator will be proportional to its frequency. In principle, this can be applied to the microwave case in a manner shown in Fig. 4. Suppose a microwave cavity, which can be tuned by a moving plunger, is excited at some specific position of the tuning plunger by a source of microwave power until steady-state resonance conditions are established. If the power were then turned off suddenly, the fields in the cavity would attenuate exponentially with time. If, however, during a period of time which is short compared with the decay time, the plunger is moved rapidly downwards to reduce the volume of the cavity, then the work done on the cavity (as shown by analogy with the pendulum) will result in an increase of the frequency of oscillation and in the generation of electromagnetic energy. (As in the case of the pendulum, the reduction of the cavity volume must be adiabatic—that is, the change in length of the cavity must be small during a single cycle of oscillation.) It is easily demonstrated that the mechanical deformation of a microwave cavity by this process is completely out of the question because of the extreme velocities needed. However, Linhart suggests the use of a plasma phenomenon which seems to have the proper characteristics for the problem. He believes that a column of plasma (indicated graphically in Fig. 5), produced by ionization of some suitable gas by a second electron stream, can be excited as an electrical resonator and would have very low losses. (This suggestion is believed to be due originally to Fainberg of the U.S.S.R.) If the electrons of the plasma column are suddenly accelerated, the resulting electron current creates a magnetic field around the plasma which causes the electrons to converge radially, or to "pinch." During this pinch, the inward motion of the electrons produces the desired rapid decrease of size of the plasma resonator and should result in the phenomena described above in terms of the mechanical tuning of the cavity. Research along these lines is currently being pursued by Linhart and his associates.

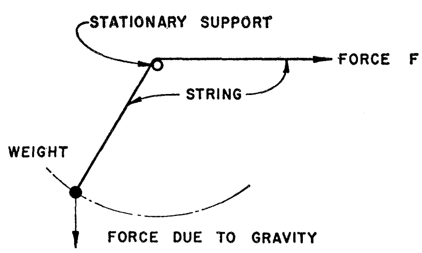

Fig. 3. A pendulum which, by shortening of its length, demonstrates the adiabatic principle of frequency multiplication.

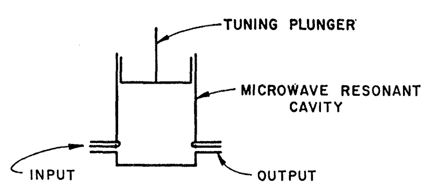

Fig. 4. Application of pendulum principle to a microwave case; the motion of the tuning plunger compresses the stored energy and increases the frequency of oscillations.

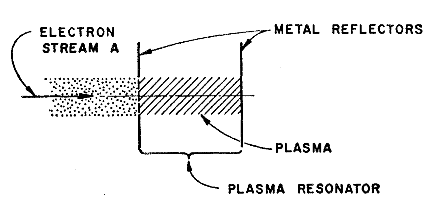

Fig. 5. The use of plasma as a microwave resonator.

Still other ideas which make use of plasma phenomena are being considered by workers in several countries; these are all speculative, since the characteristics of plasmas are still only partially understood.

Novel Methods of Amplification

In all conventional amplifying devices, including the triode, the klystron, the traveling-wave tube, and others, direct-current power is converted to radio-frequency power by first accelerating electrons from rest and then removing a part of the kinetic energy of the electron stream by exposing the electrons to radio-frequency fields in the output section of the amplifying device. Although this basic process can be executed in a number of useful ways, all of these have certain fundamental limitations, as previously mentioned. Two of the basic difficulties encountered with all electron devices are as follows: (i) Even in the absence of an input signal, all electronic devices produce an output, which is usually referred to as "noise." This is due to the fact that charged particles (that is, electrons) induce electrical signals in the output circuits due to random emission from the cathode and random variation in their velocity. (ii) Electrons even at the highest practical voltages have velocities which are not large enough to permit instantaneous interaction with radio-frequency fields; as in the triode, the "transit-time" effects preclude the extension of known techniques above a certain frequency limit.

Electronic devices of this sort are not, of course, the only means of generating electromagnetic energy. The generation of visible light is a familiar example of a process which is considerably different. In this case (to use the terminology of classical physics), electrons in one orbit can be transferred to a higher one by excitation (as in gas discharge), and this will result in emission of light when the electron spontaneously returns to its original orbit. This process demonstrates the principle of conversion of energy (in a gas discharge, from a direct-current source) to electromagnetic form by the use of electrically neutral atoms. In

Table 1. Frequency and wavelength of electromagnetic radiation that can be expected from the various types of atomic, nuclear, and magnetic transitions.

Type of transition	Representative change in energy (electron volts)	Corresponding radiation: Frequency (Mcy/sec)	Corresponding radiation: Wavelength (cm)
Atomic-electronic transitions (visible light)	~ 2	6×10^8	0.5×10^{-5} (5000 A)
Molecular transitions:			
Vibrational	10^{-3}	2.5×10^5	1.2×10^{-1}
Rotational	10^{-4} to 10^{-5}	2.5×10^4 to 2.5×10^3	1.2 to 12
Paramagnetic ions (orientation of)	10^{-4} to 10^{-5}	2.5×10^4 to 2.5×10^3	1.2 to 12
Nuclear moments (orientation of)	$\sim 10^{-7}$	25	1200

terms of contemporary theories, it can be said that a neutral atom can radiate a quantum of energy in undergoing the transition from one allowable energy state (orbit) to another allowable state. It has recently been demonstrated that this principle can also be applied to both the generation and amplification of microwave power. Since this process does not use charged particles, but rather neutral atoms, it is possible to visualize devices which would have the same sources of noise and would considerably increase sensitivity in the detection of weak signals.

To understand the possible application of this principle to the generation and amplification of microwave frequencies, it is first necessary to consider the separation between energy states in molecular, atomic, and nuclear structures. According to quantum theory, the motions of electrons in atoms, of atoms in molecules, and of fundamental particles in nuclei are restricted in a manner which results in discrete energy-state levels (analogous to the classical concept of electron orbits in atoms). The excitation of an atom or a molecule can change its state from one level to another, and radiation of energy will take place upon return to the original state. According to the Einstein equation,

$$\Delta W = h\nu$$

where ΔW is the energy change, h is Planck's contant, and ν is the frequency. If W is measured in electron volts, and ν in megacycles per second, this relation becomes

$$\Delta W = 4.14 \times 10^{-9}\nu$$

Table 1 shows a few of the possible types of transitions together with typical values of energy changes which can be expected in such transitions. The last column in the table shows the frequency and wavelength of the radiation which results from such transitions. From this table it can be seen that rotational molecular transitions can be expected to generate radiation in the microwave range and vibrational types of transitions in the millimeter (and shorter) range.

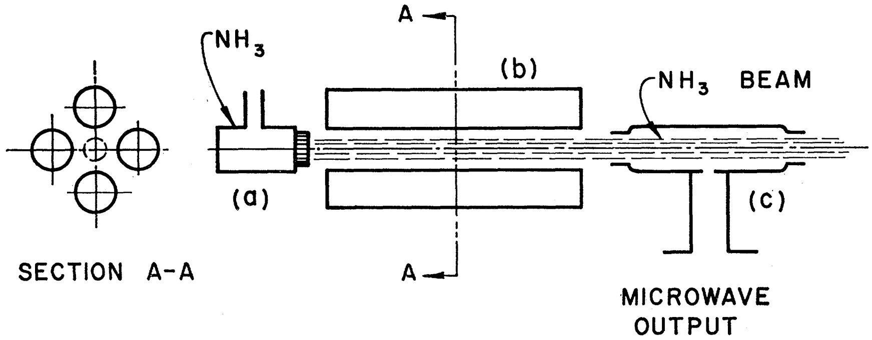

Fig. 6. Schematic diagram illustrating the principle elements of a device for generating or amplifying microwaves without the use of electron beams. (*a*) Shows the "source" of ammonia gas through which the gas diffuses through small tubes; (*b*), the "focusing elements," whose cross section is shown at the left; (*c*), the microwave cavity and the output waveguide.

That emission of radiation from a molecular system is possible does not, in fact, mean that this can be accomplished as simply as generating visible light by excitation of atoms in a gas discharge. To understand this, consider a molecule with two energy states between which transitions can occur. If the molecule is in the lower energy state, it can absorb microwave power and be raised to the high-energy state; if it is in the higher state, it can radiate the energy in the process of transition to the lower state. It turns out that the probability of these processes occurring is the same, and in a body of gas or other material with equal population densities of the two states, the radiation of energy is impossible. In the actual case, with common materials at thermal equilibrium, there is an excess of lower-state molecules, and the medium can only absorb radiation. This fact has been well known and it explains why molecular radiators have not been developed until a short time ago.

Recently, suggestions of Townes at Columbia University and of others have changed this picture. They have demonstrated that it is possible to separate the energy states to provide a region in space where an excess of molecules in the upper state, capable of emission of radiation, can be made to exist. A device of this type, called a "maser," may be of interest since it is the first and still the clearest demonstration of an important new principle. (The word *maser* has been derived from "*m*icrowave *a*mplification by *s*timulated *e*mission of *r*adiation.")

A schematic diagram of the principal elements of the Townes maser is shown in Fig. 6 (the walls of the vacuum chamber which surround the entire apparatus have been omitted). Although any one of a number of gases can be used, Townes selected ammonia for his experiments because the transition frequency occurs in a convenient microwave region, and because the population-density difference in one pair of states happens to be particularly large. Ammonia gas at reduced pressure is introduced into a box, called the "source," from which it diffuses through an array of small tubes to form a molecular beam, as indicated in the diagram. The beam then passes between sets of rods, called the "focuser," in which alternate rods are connected together electrically, with a high electrical potential applied to the adjacent rods from a direct-current source. Although the focuser does not supply any electrical power to the system, it does two things: As the molecules drift between the rods, the presence of the electric field causes the molecules to become polarized in the form of electric dipoles and, as a result of this, causes many of the lower-state molecules to be defocused and removed from the system by outward radial drift. The beam which finally enters the last region of the maser, the microwave cavity, therefore contains an excess of molecules in the upper state and is in the proper condition to radiate this excess energy. If the number of upper-state molecules sufficiently exceeds the number of lower-state molecules, the radiation from the former can create a field in the resonant cavity which can be extracted for use by means of microwave waveguide, as shown in Fig. 6. The frequency of operation of the maser, as built by Townes, is 23,870 megacycles, and this can be shifted by only a small amount by tuning of the cavity or changing of the focusing voltage.

If the ammonia beam current is too low, the device will not oscillate. In this case, however, the maser can be used as an amplifier. Due to the presence of the ammonia current, the losses in the microwave cavity can be made to be negative, and a signal sent into the cavity can be reflected in amplified form. Since the ammonia amplifier does not employ charged electrical particles, there is no noise of the conventional sort induced in the microwave cavity. Recently, measurements by Helmer, at Varian Associates, have shown that the ammonia maser, when used as an amplifier, has only about twice the noise level expected from an "ideal" amplifier.

Although the ammonia maser is potentially very useful as an amplifier, and also as a source of extremely stable microwave frequency, it does have certain characteristics which limit its use in many important applications. The principal difficulties with the maser are as follows. The electrical bandwidth of the maser is very small—in the neighborhood of a few thousand cycles—which limits its application to those cases where the information is narrow-band. Amplification by the ammonia maser occurs at a fixed transition frequency, and the device cannot be "tuned" to other microwave frequencies (except, of course, to other discrete frequencies at which different molecular transitions are possible). Due to the limited current which can be obtained in a molecular beam, the power output of the maser is very low, in the neighborhood of 10^{-9} watt. In many applications of practical importance, one or more of these limitations represent a serious obstacle.

It appears, however, that there are other possible methods which might be used to separate energy states in a medium to create a situation conducive to transitions in the microwave region. For example, it is possible to expose certain solid materials to microwave radiation of one frequency to equalize the population densities of two energy states (one of which at room temperature has very low population density) and to induce a transition from one of these to a third energy level. This process, currently referred to as "pumping," can be accomplished by a number of methods and promises to provide many combinations suitable for application in the microwave region. A combination of such pumping methods, the splitting of energy levels by means of static magnetic fields, and the use of materials with suitable properties represents a field of research of great importance, from which amplifiers of near-maximum sensitivity might be expected to arise.

High Power and Large Bandwidths

Despite the fact that microwave devices have already proved capable of very high power generation over very broad bandwidths, there are still two kinds of reasons for trying to exceed the performance of the presently available devices. The first of these is a specific one: There are a number of immediate applications which can profitably employ higher power or larger bandwidths, or both. For example, in both radio communications and in radar the use of higher power permits communication over a greater distance and with greater reliability; in particle accelerators, higher power produces greater particle energies, and this, in turn, makes possible new experiments in high-energy physics. The second reason is a more general one: In working toward higher power, one finds various difficulties not previously encountered. The study of these difficulties sheds light on the ultimate limits which can be attained and yields information which is useful in improving the performance of devices which operate below the maximum power limits.

Large bandwidth is desirable for a variety of reasons, all related to the fact that it is becoming increasingly necessary to be able to transmit and to receive greater amounts of information in a given time. There are many reasons, too specific and detailed to be listed, which justify the search for greater intelligence-handling capability of both transmitting and receiving systems. In receiver work, extensive research carried out during the last ten years has resulted in design of a number of types of traveling-wave tubes which are either now available or are known to be possible. These tubes typically have bandwidths on the order of

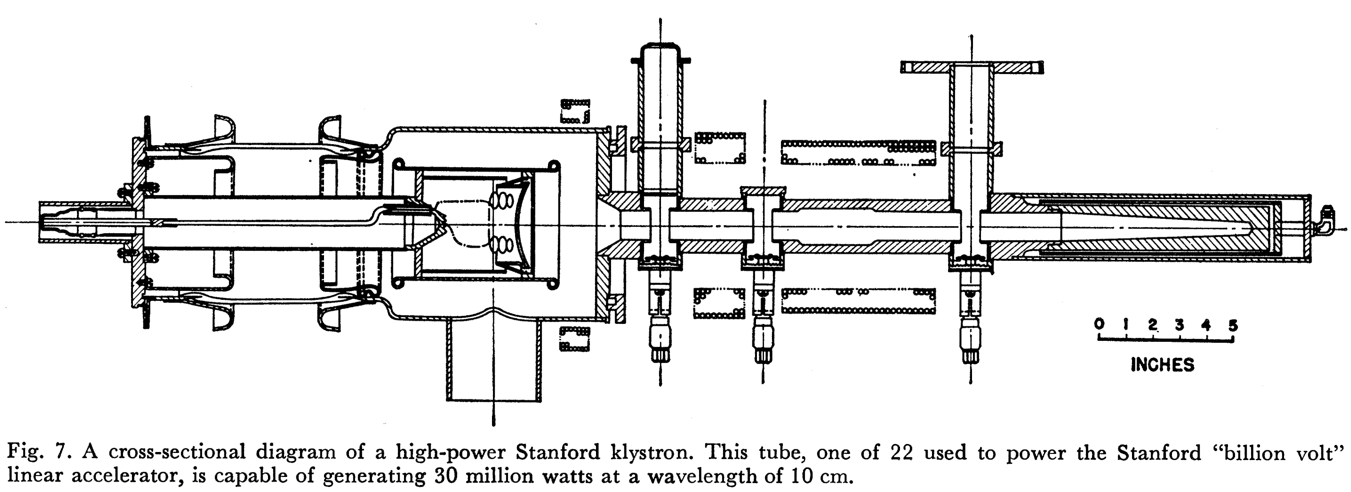

Fig. 7. A cross-sectional diagram of a high-power Stanford klystron. This tube, one of 22 used to power the Stanford "billion volt" linear accelerator, is capable of generating 30 million watts at a wavelength of 10 cm.

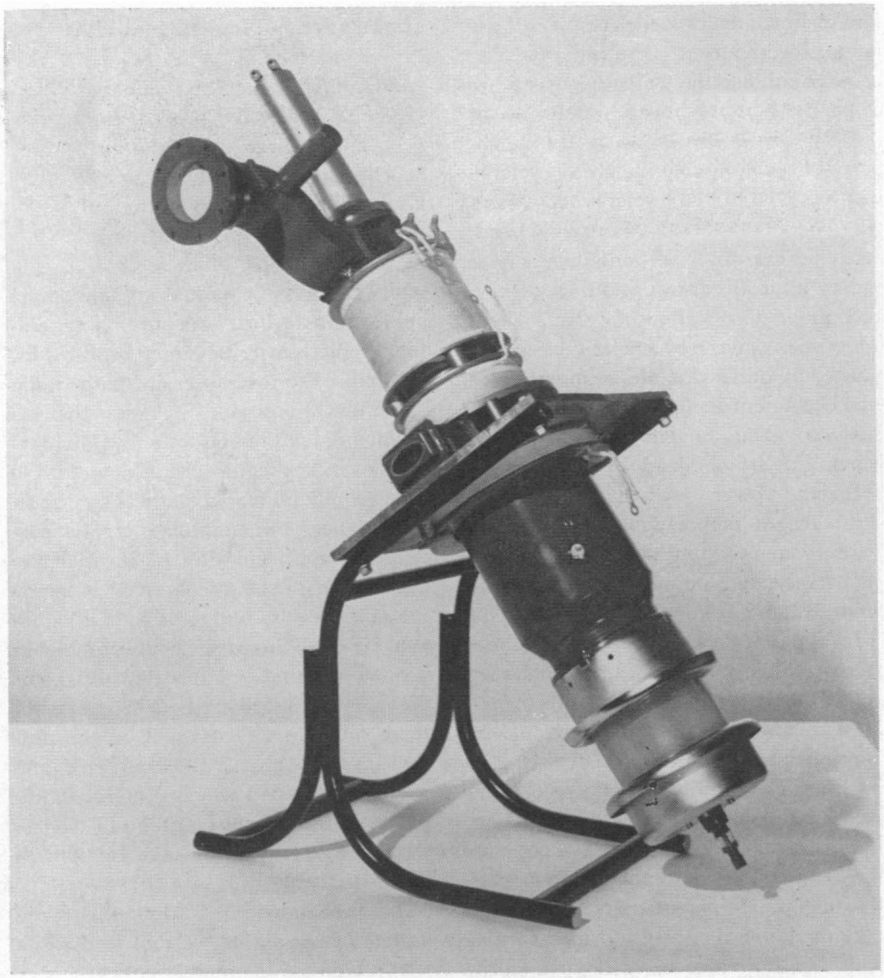

Fig. 8. The high-power Stanford klystron illustrated schematically in Fig. 7.

30 to 50 percent, and nearly the whole microwave spectrum is covered by the series of tubes now available. However, in many applications it is not sufficient to be able to receive information over a large bandwidth, and the problem of generating power over a large bandwidth has many aspects which remain to be solved.

To illustrate the current research activity in these two areas, an example of each will be given below. These are representative of the efforts now being made in the laboratories in several nations.

High power. The highest peak power generated by a microwave tube to date is believed to be 30 million watts, produced at a wavelength of approximately ten centimeters by the klystron tubes which are used as sources of power for the Stanford billion-volt linear electron accelerator. A cross-sectional diagram and a photograph of this tube are shown in Figs. 7 and 8, respectively. In its principal features this klystron differs very little from the basic one shown earlier, in Fig. 1. To generate this power, the klystron used an accelerating potential between the cathode and the anode of approximately 360,000 volts, with an electron current of about 215 amperes. The power input to the klystron, therefore, approaches 80 million watts, not far from the electrical power used continuously by a medium-sized city. This power cannot, of course, be generated continuously but is obtained in pulses of a few microseconds' duration, repeated a few hundred or thousand times a minute. The power generated by the klystron is extracted by the last cavity and transmitted to the useful load by means of the waveguide shown through a ceramic or a glass "window," which isolates the vacuum in the klystron from the external atmosphere. In operating klystrons of this sort near their peak power limit, several difficulties are encountered. Some of these are described below. They represent several of the areas of major interest at the present time.

It is found that the "window" through which the microwave power passes often fails through being punctured (this spoils the vacuum inside the klystron). The processes in these punctures are not as yet clearly understood, although they seem to be related to the unavoidable irradiation the window receives from x-rays and electrons. The work thus involves an attempt to understand the exact mechanism of electrical failures of dielectric materials when subjected to irradiation, and also an attempt to solve the problem by finding materials with greater resistance to such radiation, or by finding practical methods of shielding the windows. A second problem in the operation of present tubes is electrical arcing in the anode-cathode region. Other work is concerned with study of cathode materials which might provide longer tube life and more reliable emission.

The research activity noted above involves, to a large degree, study of the characteristics of materials when subjected to unusual conditions: electrical stress at high frequencies, exposure to x-ray and gamma radiation, and so on. Progress in this field is necessarily slow since it requires the combined skills of chemists, physicists, metallurgists, and engineers, in addition to a long and expensive program of material research and testing.

A more specific microwave problem has to do with the efficiency of conversion of direct-current power to radio-frequency power in microwave tubes. Efficiency of operation becomes increasingly important as power levels increase, since power lost in heat becomes more expensive to consume and to supply. The basic design principles of klystrons, despite many years of experience, are not yet completely worked out because of the complex behavior of electron streams of high density when subjected to magnetic-focusing fields and radio-frequency forces. These complex questions are now being analyzed, with the assistance of large computing machines.

Large bandwidth. As an example of the research being carried out to extend the bandwidth capability of high-power transmitting tubes, a high-power broadband traveling-wave tube currently being developed at Stanford University is shown in Figs. 9 and 10. In its general configuration the traveling-wave tube resembles a klystron, having an electron stream which passes through a series of cavities. The main difference between the klystron and the traveling-wave tube is the following: The klystron uses a limited number of cavities, each one being simply a resonant circuit, and these are adjusted independently to respond to the frequency which one is trying to generate or amplify. The traveling-wave tube, of the type being discussed, has a number of cavities which are coupled together electrically to form a transmission circuit through which an electromagnetic wave can propagate from one end to the other. As the wave travels through the circuit it exposes the electrons in the beam to relatively weak electric forces, but for a protracted period of time. During this period of exposure, accumulated forces upon the electrons cause them to bunch and eventually to deliver power to the output terminals, much as with a klystron. Because a high degree of resonance is avoided by the use of tightly coupled electrical circuits, the electrical bandwidth of the traveling-wave tube can be many times that of a klystron.

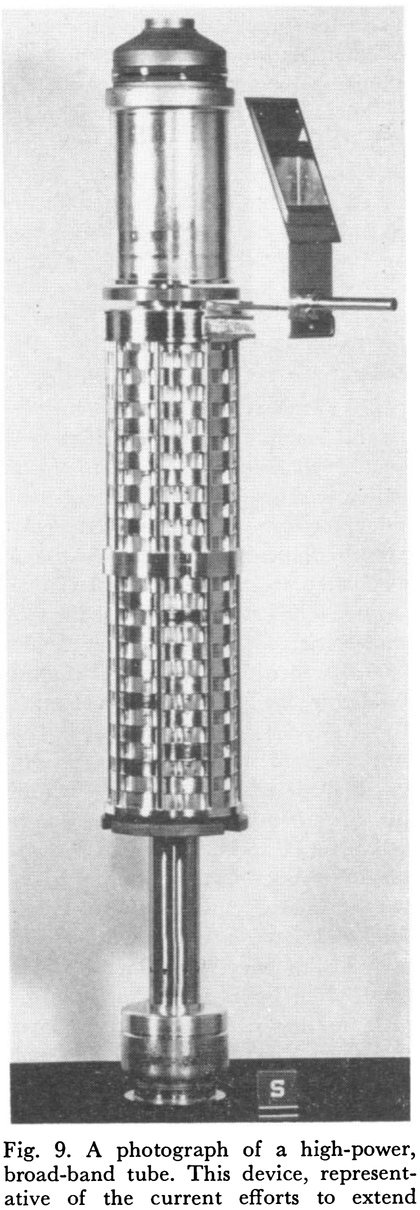

Fig. 9. A photograph of a high-power, broad-band tube. This device, representative of the current efforts to extend the bandwidth of microwave high-power tubes, is being tested by M. Chodorow and associates at Stanford University.

In order to make a satisfactory traveling-wave tube of the kind shown, it is necessary to design the assembly of cavities as if it were an electrical filter, and also to control the propagation velocity of the waves through the structure so that it will match the velocity of the electron stream. It is further necessary to arrange the fields in the cavities so that the electrons are exposed to the highest possible electric fields. These requirements cause the configuration of the cavity structures to become highly complex, so that understanding the behavior of such structures requires extensive experimental work and complicated analysis. Development of adequate theory for these kinds of microwave structures, experimental design of suitable cavity elements, and a great number of other practical problems still remain to be resolved before tubes of this class can be said to be fully understood and ready for practical application.

Conclusion

It is instructive to consider, in historical perspective, the way in which the microwave region of the electromagnetic spectrum came into use. During the 1930's, the "transit-time" of electrons, associated with conventional radio tubes, and the size requirements of circuit elements appeared to impose a fundamental limitation on the frequencies which could be used. This limitation was overcome by the development of resonant cavities and the formulation of the principle of velocity modulation. Thus, the microwave region was opened up, and with it came rapid development of new devices and new principles which have made possible important advances in communications, navigation, radar, particle accelerators, and a number of other fields which were not foreseen by the

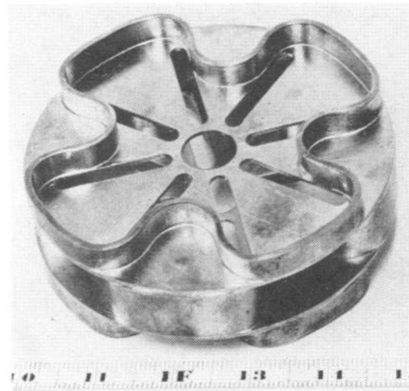

Fig. 10. A section of the "circuit" of the high-power broad-band tube shown in Fig. 9.

workers in the field. In like manner, extension of the usable electromagnetic spectrum into the millimeter and submillimeter region seemed, until recently, to be extremely difficult, if not impossible. With increased insight into such phenomena as molecular transitions, however, this limitation, too, appears now to be artificial. Work in this new field gives promise of developments which will also have great importance. The significance of this historical development seems sufficiently clear: the reservoir of knowledge fed by research almost inevitably flows over into new fields and new applications and provides methods by which still further knowledge may be acquired.

The examples of current research listed in this paper cannot do justice, of course, to the intensive and varied research being pursued in many of the laboratories throughout the world. Not mentioned, for example, is the very important possibility of extending the findings of semiconductor research to the microwave region. Suggestions have already been made which may extend the present high-frequency limit of the conventional transistor and would permit the development of related devices at microwave frequencies.

It is my hope that the description of the accomplishments, applications, and current problems in this field of applied research is sufficient to demonstrate that the future of this work holds as much promise as it held for the pioneers of the microwave field in the mid-1930's.