Microwaves—A Review of Progress in Great Britain During 1960*

A. E. KARBOWIAK†

Summary—The fields covered by the review are: Electromagnetic theory as applicable to wave propagation, theory of waveguides and components, microwaves in fundamental measurements (such as time and atomic constants), designs of components, measurements, solid-state devices and a summary of utilization. Future trends are also indicated. The review (with some exceptions) does not cover the following fields: Antennas, propagation and microwave tubes. In reviewing technical publications, preference is given to such aspects of work which are novel, fundamental or are of controversial nature or are likely to influence future trends; where appropriate, criticism of the work is given.

Introduction

MICROWAVES is a term (now almost generally accepted) which stands for a vast field of activity. Indeed, so vast that many of us who have been active in it for many years have been surprised by its tremendous rate of growth. Not surprisingly, therefore, one finds that a substantial proportion of published scientific papers, public lectures on science and various aspects of engineering (not only electrical) as well as subjects on utilization, directly or indirectly concern microwaves: microwaves *per se*, and microwaves for fundamental measurements on atomic and material constants. The most precise measurements of length and time involve microwaves and *vice versa*, for some microwave uses, the skill of the mechanical engineer is tested to the full. Microwave power from fractions of a microwatt to many megawatts and frequencies corresponding to wavelengths from decimeters to fractions of a millimeter is now a common practice.

Industries of diverse interests call on microwaves as the new source of power since microwaves, when liberated in the form of heat, can be applied with precision in the quantity and place required. Greater and greater powers also become available for communication purposes and this brings an investigation of industrial, biological as well as medical aspects of microwave radiation into prominence.

Parametric amplifiers and masers are the fruits of research carried out during the last decade and they are often applied in the fields of radio astronomy and communications. In fact it is said that there has never been so much interest in liquid helium as there has been since the advent of low noise receivers!

For applications involving microwaves in communication systems, as well as in fundamental research, there is a trend towards higher and higher frequencies, yet lack of suitable sources of power in the millimetric and submillimetric bands besets any rapid progress. Microwave tubes are inefficient, have short life and are not a commercial proposition in the short millimetric band. But, for submillimetric frequencies harmonic generators are the only sources of monochromatic power. These are inefficient and progress is slow and doubtful. Not surprisingly, new solid-state devices of unspecified nature are the hope; the stakes are high but odds are equally high. This is a field for fundamental research and so is the whole field of generation of coherent radiation in the band from submillimetric waves through infrared to frequencies corresponding to the visible spectrum. Are we going to include this entire field under the auspices of microwaves, particularly since our many measurement methods of the higher microwave frequencies already resemble those of optics?

It is fitting to observe that among the many conventions, conferences and international meetings which have taken place in Great Britain during 1960, three in particular were concerned, within their own spheres of interest to a larger or smaller extent, with microwaves. These were:

1) The XIIIth General Assembly of URSI held at University College, London, Eng., September 5–15, 1960.
2) A Conference on Solid State Microwave Amplifiers held at Nottingham University, Eng., April 6–8, 1960.
3) The 3rd International Conference on Medical Electronics held at Olympia, London, July 21–27, 1960, under the auspices of the IEE and the International Federation for Medical Electronics.

Work in the microwave field can conveniently be reviewed under the following headings:

1) Investigation of fundamentals of physics such as measurements of length and time and atomic and material constants.
2) Investigation of fundamentals of electromagnetic waves.
3) Development in microwave components and measurements.
4) Generation of microwave radiation, in particular solid-state devices.
5) Propagation and antennas.
6) Utilization including industrial applications and communication systems.
7) Future trends.

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† Standard Telecommunication Labs., Ltd., Harlow, Essex, Eng.

The above topics cover an immense territory of our knowledge of which only a part was chosen for this review.

Under item 1 a great deal of work done in physics, such as spectroscopy, could be listed but because of its very specialized nature it will be omitted from further discussion. On the other hand the measurements of length and time deserve a mention, because such measurements are fundamental.

Study of microwaves and waveguides has always involved a great deal of electromagnetic theory and not infrequently progress in the field of microwaves was a direct result of deeper understanding of electromagnetic theory; a step forward in the electromagnetic theory is always a step forward in the field of microwaves.

Progress in microwave components and measurements is usually of the nature of an improvement or extension in the existing knowledge and consequently no detailed discussion of such work will be given here. Nevertheless, such contributions are building-blocks of microwave techniques and some references are therefore included.

Any progress in the generation of microwave power, particularly in the upper frequency band is of utmost significance in further progress in the microwave field; but progress in conventional microwave tubes has been extensively reviewed recently by Harvey [1]. This review will be chiefly concerned with generation of microwaves using solid-state devices, a fascinating field full of vague promises.

Propagation and antennas is a subject intimately related to the activities of URSI and progress in this field can be gathered from the many excellent reports of the XIIIth General Assembly, which took place in the autumn of 1960. Mention should be made however of the work by Belatini [2] which does not seem to have received any publicity. The work which concerns tropospheric scatter phenomena, deserves attention because there exists a considerable disagreement over the exact process of the scattering phenomenon. Belatini observes that the field received beyond the horizon shows an almost regular spatial interference pattern, implying that incoherent scatter cannot be the mechanism responsible, as is so widely accepted, for signals received beyond the horizon. The author's thesis is that the heat from the sun is responsible for vertical motion of air producing in effect torus-shaped "Bénard cells." These cells act as weak biconcave lenses causing the radio waves to diverge in the vertical plane and in this way enable radio signals to reach beyond the horizon. The hypothesis is not only original, but the evidence against "tropospheric scatter" is strong and the evidence for Belatini's theory good.

Industrial applications, and communication systems in particular, are the important uses for microwave equipment. Much of the interest and financing of research in industries is taking place because of such applications. The existence of research, therefore, hinges to a large extent on possible industrial and commercial applications although research *per se* is being accepted on a larger and larger scale. Microwave links are, to a large extent, the main commercial interest, but, in addition, numerous defence projects such as radar, etc., occupy the activity of many. But new communication systems such as long distance communication by waveguide and satellites occupy the imagination of many. Some other industrial applications have been discussed adequately by Harvey [3].

Assessment of future trends, which is of great importance to industry and those responsible for planning future activities, involves a specific form of crystal-gazing. But, there is one certain lesson that we can learn from the past: few things in life are less predictable than the activity of a research worker; in fact the game is so speculative that staking a Derby winner is not an unjust analogy!

This review is primarily concerned with work which in the opinion of the reviewer is either of a fundamental nature or is likely to have a significant impact on the progress in microwaves, has features of novelty or is simply fascinating.

Fundamentals

A concise review of progress in electrical units and standards has been prepared by Vigoureux [4]. It transpires that the fundamental units of electricity and magnetism can now be measured with a reproducibility of about 1 part in 10^6 using electrical measurements on constants such as gyromagnetic ratio of the proton.

Length and time—the two fundamental units—can be measured and the units maintained and reproduced to a much higher order of accuracy than was possible only a few years ago. The measurements are carried out in electromagnetic spectrum; but whereas the "standard of length" is conveniently found in the visible spectrum (for example, the wavelength of the orange line of krypton—86), the most accurate "clock" operates at a fundamental frequency falling in the microwave band. The caesium frequency standard which operates at about 9.2 Gc, is a result of three or four years of research carried out in various countries.

In Great Britain there are now a number of caesium clocks in operation following the fundamental work carried out by Essen and Parry at the National Physical Laboratory [5]. Such clocks operate with an error not exceeding about 1 part in 10^{10}.

In March, 1959, the International Committee of Weights and Measures adopted the second of Ephemeris Time as the official standard. The astronomical standard, however, cannot be reproduced to better than about 1 part in 10^9, even when averaged over a period of several years. The caesium beam standard, on the other hand, is readily available and there is a possibility that the second of time may be defined in terms of frequency of an atomic frequency, and this lies in the microwave band.[1]

Quartz crystal oscillators are still a very convenient intermediary between the caesium clock and astronomical observations. But with the recent developments in the atomic frequency standards and also MSF transmissions in the United Kingdom and Western Europe, the quartz crystal oscillators are likely to become superfluous.

Present work on atomic frequency standards is concerned chiefly with design of more compact units (some so small that they can be fitted inside rockets or installed inside an artificial satellite), study of different designs, sources of errors and intercomparison of measurements. There is at present an unresolved discrepancy of about 2 parts in 10^{10} between clocks of different type or build in different countries [6].

A characteristic feature of many meetings or lectures concerning microwaves is that the subsequent discussions are frequently diverted towards the fundamentals of electromagnetic theory. There again one is frequently involved in discussion on basic units [7], or even the choice of coordinate systems and nomenclature. The opinions are frequently diverse and sometimes no conclusions are reached. This is all to the good, yet nevertheless a little surprising, for it is an outward sign of an inward uneasy feeling about the fundamental concepts. Most of us, at one time or another, when engaged in an investigation of an advanced nature have experienced a feeling of complete standstill, only to find out that the root of the trouble was inadequate comprehension of fundamentals and not the apparent complexity of the particular problem on hand. We should, rightly so, have a look at our fundamental formulas and examine them from time to time in the light of gathered experience. It is reassuring to find that this spirit is prevailing and our concern about the fundamental concepts is a healthy one.

The Department of Scientific and Industrial Research has issued a booklet containing tables [8] of the refractive index of air for a wide range of temperatures, pressures and water-vapor pressures based on formulas derived by Essen and Froome.

Theory of Wave Propagation and Waveguides

The foundations of waveguide theory were laid down more than half a century ago by Lord Rayleigh, but it was the widespread adoption of the powerful analytical techniques from the field of quantum mechanics directly to microwaves that led to the elaboration of waveguide theory as we know it today. In principle, therefore, any imaginable wave-guiding structure could be analyzed in detail, yet it would be a gross overstatement to say that there is fundamentally nothing new that could be discovered. For there is more to understanding than mere writing down of general mathematical expressions. One must be able to comprehend what the mathematical expressions stand for and be able to formulate useful physical pictures before a clear physical interpretation can be given; and later on one must be able to apply it to the design of a particular structure, be it a single component or a complete communication system. It is clear that during the last few years we have progressed towards that goal, but we have not reached it entirely. Indeed, it is doubtful if such an ideal state of understanding can ever be reached. But, it is only through discussion, analysis, and a continual examination and re-examination of our accumulated facts that a progress towards unification of our knowledge can be made. At the same time we may be able to derive some enjoyment from it.

There are two outstanding aspects of the theory of waveguides: 1) propagation in waveguides with walls other than perfectly conducting, and 2) propagation in nonuniform waveguides.

Propagation in Homogeneous Uniform Waveguides

The two above mentioned factors have one thing in common: we do not seem to be entirely sure what the best way is to describe an electromagnetic field inside a waveguide and how such fields should be classified. A particular case is that of surface waves.[2]

Some contributors, in their own way, maintain that a rational unified and useful classification of waveguide modes is possible. Thus, Karbowiak [9] shows quite generally that the electromagnetic field can be conveniently resolved into pole waves and branch-cut waves; but in addition he also introduces the concept of a quasi-mode. The findings can be briefly summarized as follows.

To every cylindrical waveguide, there corresponds [10] a certain infinite but discrete distribution of poles in the complex plane of the propagation coefficient, γ, and one or two branch points (usually only one) depending on the number of geometrically possible infinite directions, in the transverse plane of the waveguide. Integration around the branch-cut yields the branch-cut wave, and the poles represent the possible modal (or guided wave) propagation. This picture is agreed on by most workers in the field. Karbowiak however accepts for the definition of a pole wave the following function: $\psi_i = a_i \cdot f_i(u, v) \cdot \Lambda_i \cdot \exp(-\gamma_i z)$, where a_i is the amplitude coefficient, $f_i(u, v)$ a function describing the field pattern in the waveguide transverse plane and Λ_i a multiplier, which is related to the

[1] The implied great faith in the stability of atomic vibrations, which we seem to cherish, cannot be overemphasized, particularly since our knowledge in connection with atoms and molecules is still so new.

[2] It was the function of a Study Group of Commission VI of URSI to try to discuss various types of surface waves with a view to classifying them. But, it transpired that there are nowadays so many variants of surface wave concepts that a useful definition could not be formulated. It was agreed that to pursue the matter of terminology applied to surface waves would be unprofitable.

complex Fresnel Integral. This definition differs from the more commonly accepted one by the multiplier Λ. If $\Lambda=1$, then the expression defines a quasi-mode. The point of such a definition will transpire from an example.

Imagine a waveguide with a given geometry and excitation having arbitrary but physically realizable walls. Then in the plane of γ there will be a distribution of an infinity (discrete) of poles and, say, one branch point. Of the poles, some will be placed on the right and some on the wrong Riemannian Plane [10]. The quantity Λ will be close to unity for all poles on the "right" plane and it will be very nearly zero for poles lying on the "wrong" plane. But, Λ is a continuous function of frequency and parameters describing the physical medium and, therefore, if either of these quantities is gradually varied, then the poles will move from place to place and the value of the multiplier will vary. Some poles, however, will pass gradually through the branch cut onto the other Riemannian plane, but the total number of poles will remain unaltered, and, therefore, all pole waves exist provided the excitation is such that a_i is finite. The constitution of the field changes continuously, because depending on the value of the multiplier Λ some pole waves become more significant than others. If we were to expand the field in terms of functions with $\Lambda=1$ then clearly the modes would either exist or not depending on whether the pole were just to the left or the right of the branch cut. Since all events in nature are continuous such a classification could not be recommended. Yet, functions with $\Lambda=1$ are useful in describing fields in finite regions and for such modes the term quasi-mode is reserved; modes of this kind need not, on their own, be a solution to the waveguide problem, but in *finite* regions (of interest) the field may very closely approximate such modes and hence their significance. A leaky wave is one example, a Zenneck wave another.

Some investigators, however, do not share Karbowiak's viewpoint. Barlow [11] for example, proposes to classify electromagnetic waves into three types: 1) TEM waves, 2) surface waves and 3) so-called wave guide modes. Such classification, while having the merit of apparent simplicity, would be rather restricted, as pointed out recently by Waldron [12]. Because, if we consider the pole representing (say) the TEM wave in a perfect waveguide, then as we change gradually the perfectly conducting medium and make it imperfect, the pole will move slowly away from the imaginary axis and the associated Λ will become a little less than unity. Eventually, if the properties of the media are sufficiently altered, then the mode will not in the least resemble the TEM mode. The wave due to that particular pole may even be more like some other mode or even form a hybrid with one of its neighbors, etc. As a pole wave, however, it exists all the time, though for some properties of the media it may appear as one quasi-mode and for some as another.

Surface waves in various forms have always been a fruitful field for research—surface waves for transmission lines or for antennas, surface waves for measurements on materials and surface waves for their own sake.

Clarricoats has made an interesting and exhaustive study of wave propagation along dielectric rods [13]. In the past, several investigators have analyzed propagation of selected modes on dielectric cylinders with and without a concentric metallic shield. In this study, however, the author was able, through a detailed analysis, to show how the various modes (which sometimes are very complicated) are related to each other and how the mode spectrum is affected by the cross-sectional dimension of the rod and the proportions of the metallic shield. This is yet another example of a unification of the concept of modes and a greater understanding of the structure of electromagnetic field. A graphical method of evaluation of propagation coefficients is given and application of the results to ferrite devices is also indicated.

The particularly interesting feature of the analysis is the physical picture. The mode spectrum of the structure can be followed step by step as the diameter of the dielectric rod and the diameter of the metallic shield are varied. In fact, the modes of an empty cylindrical waveguide are linked to those of a shielded dielectric rod and these in turn are related to those of an unbounded dielectric rod, the surface wave modes. It would be interesting to analyze the excitation problem in such waveguides. From such an analysis, we venture to guess, it would transpire that there is a branch-cut wave representing the radiation field, and a discrete infinity of pole waves. The pole waves would always be present but their proportion in the total field and their character would vary as the proportions of the dielectric rod and the metallic shield were varied. In this way modes of one waveguide could be related to modes in another waveguide by a continuous process without any ambiguity. Furthermore, over certain finite regions some of the modes (quasi-modes) would be appreciable and some other modes would be negligible (the quasi-mode would have no physical significance).

A number of other surface wave modes and supporting structures have also been analyzed. The hybrid EH_{11} mode of a dielectric rod has received detailed attention with a view to utilizing this mode to measurements of permittivity of samples in the form of circular rods [14]. Surface wave antennas have been analyzed on many occasions previously but Hirsch [15] has carried out an analysis of higher-order surface wave modes supported on a dielectric coated conductor. These modes are all hybrid modes and most of them are very complicated. But although such modes can have low attenuation, on suitably proportioned guides, the exploitation is difficult because of analytical complexity and lengthy computations.

Two different surface wave excitation problems have been analyzed. One by Wait and Conda [16] concerns essentially launching efficiency of a surface wave from a magnetic line source placed above a reactive surface. The novel part of the investigation lies in the extension of the analysis to launching of a surface wave over a corrugated elliptic cylinder. It is shown that for certain proportions of the cylinder strong resonance characteristics are obtained. The results, no doubt, can be extended to other structures such as radiation over the surface of a sphere. Another excitation problem was analyzed by Angulo and Chang [17]. This concerns excitation of surface waves along two infinite, identical, separate and parallel dielectric slabs by a magnetic line source. A modal analysis is carried out and an expression for the far field is obtained. Launching efficiency, radiation loss and radiation pattern are also obtained. It is shown that there exists an optimum thickness and spacing of the slabs for maximum efficiency. A surface wave problem of a different kind was analyzed by Williams [18]. He investigates the excitation of surface waves by plane electromagnetic wave incident on a wedge with surface impedancy boundary conditions. It is shown that surface waves will be excited even though the surface impedance values on the two sides of the wedge are unequal, provided that certain discrete values of the wedge angle are excluded.

There has been, and still is, a considerable amount of interest and discussions on how surface waves should be classified. But, in the opinion of the reviewer an important aspect is still not receiving adequate attention, that is, we are calling by the same name "surface wave" physically different things.[3] On one side there are the modal waves (pole waves) of propagation and these could be classified on their own. On the other side there are various types of waves associated with the radio wave propagation over the ground. We do not think that it really matters whether we call the first group surface waves and call the other group by a different name or the other way round. Provided that a distinction between the two groups (let it be three groups, if the need arises) is made, classification within the group is of secondary importance and will follow much more easily. After all, biologists, for example, do not call different species of the animal kingdom by the same name, but find it easier to differentiate between them, despite the fact that borderline cases clearly exist.

Propagation in Nonuniform Waveguides

There are many variants of nonuniform waveguides and these are discussed under three separate headings: 1) Single mode propagation in nonuniform lines, 2) Propagation in slowly varying nonuniform multimode waveguides and 3) Propagation in waveguides with statistically distributed irregularities.

[3] A good summary of the situation is given in a review paper by J. R. Wait presented at the XIIIth General Assembly of URSI.

The foundations of the theory of wave propagation in nonuniform waveguides were established by many workers in different countries (*e.g.*, Stevenson, Schelkunoff, Katsenelenbaum, Riter, etc.). The subject is very complicated, but by making various simplifying assumptions it is possible to solve a number of specific problems and to go a long way towards forming a coherent physical picture.

Problems involving only a single mode can be reduced to the problem of design of a taper between two transmission lines of unequal characteristic impedance. It is well known that Tchebycheff design leads to minimum length for a given reflection coefficient over an infinite bandwidth. But, for most applications only a finite bandwidth is required and then it is possible to design a shorter taper. Solymar shows that there is an infinity of possible solutions to tapers of as short a length as desired but that the shape of the taper would be extremely complicated (a violently oscillating function), and therefore the design would be impractical [19]. By introducing the concept of "function complexity" he was able to limit the class of functions and give design criteria of practical significance. The theoretical results are interesting in that there exists a Fourier transform relation between the shape of the taper and the reflection coefficient.

A problem somewhat related to tapers is that of bends. Here again over a given bandwidth a small reflection coefficient is specified and the problem is to design a bend as small as possible. The usual procedure is to design a binomial bend; but Wray and Hastie show that by going to the limit and taking infinitesimal sections, a considerable improvement in the design is possible [20]. The analogy with taper is striking, and one would guess that further improvement should be possible using Solymar's approach. Presumably many other gradually varying transitions could be treated in a similar manner, *e.g.*, twisted waveguides [21].

An entirely different approach to tapers was proposed by Barlow [22]. The idea is to maintain a completely undisturbed field pattern not only inside but also outside the guide, irrespective of its cross section. The method has been demonstrated by application to the H_{on} and E_{on} modes but it is doubtful whether it will be possible to extend it to other modes because physically it would be difficult to provide the required boundary conditions. We can examine the proposal by reference to Fig. 1. Here A and B are arbitrary planes extending right across the infinite pattern of the H_{0n} (or E_{0n}) mode. The planes A and B could then be replaced by suitable impedance sheets and the field outside omitted. Clearly, A and B form, geometrically, a taper, but not from an accepted electrical point of view. The reason is that the wave is not really "guided" since the energy crossing planes A and B is of the same order of magnitude as the component of energy flow along the planes. The wave pattern does remain undisturbed but the planes A and B are not surface impedance boundaries and they do not "guide" the wave. No doubt, some applications of this proposal will be forthcoming and any experimental work in this field would be of interest.

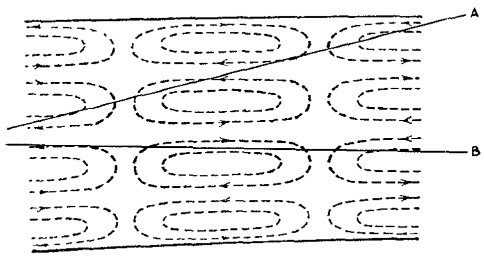

Fig. 1.

Design of mode transducers is perhaps one of the most difficult problems in the theory of nonuniform waveguides and has eluded a satisfactory solution for a long time. Such designs as have been produced have been based on engineering intuition. Solymar and Eaglesfield have recently proposed a new approach to the design of mode transducers [23]. In essence the method of design is as follows. If a mode ψ_1^A in waveguide A is to be transformed into a mode ψ_2^B in waveguide B then we form a wave function $\psi = g_1(z)\psi_1^A + g_2(z)\psi_2^B$ where g_1 and g_2 are slowly varying functions of the axial coordinate z with terminal conditions $g_1(0) = g_2(L) = 1$ and $g_2(0) = g_1(L) = 0$, where L is the length of the transducer. There is, of course, an infinite number of possible solutions and the optimum solution is yet to be discovered. For simplicity the eigenvalues of A and B are made equal by preceding either one or the other waveguide with a simple taper. The shape of the transducer is determined by zeros of the ψ function; this part of the design for all but the simplest cases is best accomplished by a graphical procedure. The authors have designed a number of different transducers and the simplest example is that of the H_{01} rectangular to H_{02} rectangular [24]. There does not seem to be any limitation to the method, and transducers so designed are all wide band. It is most instructive to work out a complete design of a transducer because it is then that one gains a deeper and clearer understanding of modes in nonuniform waveguides.

It remains to be proven,[4] but it would appear that the complete set of pole waves is undergoing a continuous transformation as one continuously changes the shape of the waveguide. There is a one-to-one correspondence between modes in one section of the waveguide and another. No new poles can be created by such a continuous process but some poles may merge into one or form hybrids, while others, which may have been presupposed to be simple poles, will split. It is not possible to subdivide modes in general waveguides into E or H modes or in any other way that would be generally valid, but one can label the modes just the same. During such a process one should not be surprised to find that a pole representing an E_{01} mode in a circular waveguide will become transformed by a one-to-one correspondence into (say) an H_{27} mode of a circular waveguide, but, if the transformation of the waveguide is carried out in a different way, a one-to-one correspondence with another mode will be established. The type of one-to-one correspondence between the modes is purely a function of the shape of the transducer.

[4] The description given in this paragraph represents the reviewer's opinion. No rigorous proof in support of it has yet been produced.

Transmission properties of waveguides with statistically distributed irregularities are of particular importance in connection with long distance communications by waveguide. Various analyses have been carried out in Great Britain and the United States during the last few years, but recently Larsen (in Germany) has prepared yet another study [25].

Waveguide Components, Devices and Measurements

The field of interest here can be divided into theoretical analysis of components and various configurations of obstacles and apertures, properties of ferrites and measurements of dielectric properties and microwave power.

Strip-lines continue to be a subject of interest [26], [27]. With most strip-line configurations, it is difficult to obtain a good correlation between theory and experiment. This is understandable because the structure, from an electrical point of view, is rather complicated. In addition, strip-line forms an open structure and, therefore, any discontinuities such as matching stub or corner cannot be calculated using conventional waveguide methods because of the associated radiation field. Some progress, however, can be made using various simplifying assumptions, but the results are understandably approximate. Assuming a substantially TEM transmission, Lewin was able to assess the properties of a post, a corner and a short circuit; he also examined the radiation patterns associated with such discontinuities [28]. He concluded that a short circuit is appreciably worse, from the point of view of radiation loss, than an open circuit. Only a few of his results, however, have received experimental confirmation to date.

The theory of waveguide junctions is now well understood through Schwinger's Variational Approach. But all waveguide discontinuities could be analyzed from first principles by matching the complete waveguide fields on both sides of the discontinuity. The matrix relating the modes is infinite, but for a single mode waveguide the elements of the matrix—which, with the exception of the dominant mode, represent only evanescent modes—is quickly convergent. Sinha used this fact and approximated by summing up just the first few terms and in this way was able to obtain the equivalent circuit parameters for a waveguide junction [29]. His formulas agree very well with experimental results.

A problem of great practical significance and yet difficult to analyze for the general case is coupling of waveguides through apertures. Some years ago Stevenson obtained a rigorous formulation of the problem, but his equations are difficult to apply in most cases. Bethe's approach is relatively simple and has been used successfully for the design of many waveguide and cavity configurations. Bethe's method, however, is restricted to small apertures only, and a new approach, to handle the numerous practical cases where large apertures are used, is clearly needed. Lewin's approach forms a useful extension to Bethe's work [30]. The idea is to use the results obtained in the antenna theory (quasi-static) and apply them *via* Babinet's principle to apertures in a waveguide wall and obtain corrections to Bethe's aperture polarizabilities. It would be difficult to deal, in this way, with arbitrary apertures but the author manages to analyze long narrow slots and also a case of two waveguides coupled by crossed slots.

The phenomenon of traveling-wave resonance has a number of specialized applications. The theory and some of its properties were investigated by Twisleton [31].

Theory of microwave propagation in ferrites is of great importance in the design of numerous microwave components such as isolators, gyrators, phase shifters, etc. But, because of the tensorial character of ferrite permeability, the general theory is crowded with difficulties. Although in a number of specific cases, useful solutions can be obtained [32]. Sometimes, even what could appear, on superficial examination, to be quite a manageable problem, seems to present difficulties. Thus, for example, the determination of the input impedance of a ferrite-filled waveguide becomes a sizable analytical problem to which only partial answers have been obtained. For certain range of parameters Lewin was able to obtain a correct solution, but outside that region the formulas lead to a physically unacceptable solution (complex impedance) and have to be rejected [33]. Recently however, by taking into account Bresler's surface waves, which propagate in the gap between the ferrite and the wall, the author was able to justify the validity of his solutions.

Various measurements on ferrites and their interpretation are yet another prolific source of mathematical problems. One of the most favored measurement methods is one in which the sample of ferrite to be measured is prepared in the form of a small sphere and is inserted inside a cavity [34]. From the measurement of the change in the resonance conditions of the cavity the ferrite permeabilities are determined. In the past a number of perturbational techniques were developed, and there have been many discussions concerning the relative merits of various methods. Underlying all theoretical formulas there are various assumptions and these have been reviewed and classified by Waldron [35].

Various measurements on waveguide components, power measurements using resistive films and Q-factor measurements have also been described [36]–[40]. These incorporate various extensions and modifications to the existing methods. A somewhat different method of measuring permittivity has been proposed by Sinha and Brown [41]. Here the sample, which is in the form of a thin rod, is inserted through a hole in the end wall of a circular cavitiy operated in the H_{01n} mode. The other end wall is formed by a movable plunger. At the desired frequency the loss tangent and permittivity are deduced, from the cavity Q factor and the change in the plunger position, as a function of the sample insertion.

In the millimetric band, yet another method of measuring dielectric properties becomes feasible; Caicoya refers to the method as the "High-Order Mode Interferometer" [42]. In essence, the method consists of transmitting a parallel beam of millimetric radiation at an angle to a parallel slab of material (under test) placed between metallic plates. From the transmission loss, as a function of angle of incidence and the geometry of the sample, the permittivity and loss tangent are deduced.

This is an illustration of quasi-optical methods in the microwave band. With the growing interest in the upper millimetric band, such methods are likely to be applied to the design of microwave components and, perhaps, of complete microwave systems [43]. General mechanical design and manufacturing techniques have been reviewed by Harvey [44], [45].

Solid-State Devices

The fields of interest here are transistors, diodes in general and tunnel diodes in particular, parametric amplifiers and masers.

Transistors are really beginning to reach microwave frequencies [46] but it is doubtful whether transistors of the types available to date will be a commercial proposition. A real success of transistors at microwave frequencies hinges on the development of new types.

It is probably true to say that none of the semiconductor devices has undergone such a rapid development and wide acceptance as has the tunnel diode [47]; yet, for microwave applications the prospects for the tunnel diode are not too bright. Currently available tunnel diodes are capable of delivering only tens of microwatts of power at the lower microwave frequencies, and although research is taking place in a number of establishments, there does not seem to be much chance of inducing a tunnel diode to deliver more than about one milliwatt of power at the lower microwave frequencies or tens of microwatts at the upper microwave frequencies. Clearly, junctions with much higher current densities are needed. This suggests the use of high mobility compounds such as gallium arsenide, indium antimonide, etc. Using wafer construction, a number of gallium arsenide diodes have been produced [48]. Although the technology of such diodes is more involved than that of the germanium diodes, these diodes are preferred for microwave applications.

Microwave parametric amplifiers and masers form a very new field. Parametric amplifiers entered the microwave field in 1957 (in the United States) through the work of Suhl and Hines but its rapid progress was made possible as a result of Uhlir's work on parametric diodes. Parallel with the diode work, ferromagnetic amplifiers and parametric beam tubes were developed. The age of maser devices is about the same as that of parametric amplifiers, but the chief impetus to the maser work was received from Bloembergen's (1958, United States) proposal of a three-level solid-state maser.

The interest in parametric amplifiers and masers quickly spread to other countries, and in Great Britain there are a number of establishments working in this field. Parametric amplifiers were discussed in a number of review articles (*e.g.*, [49], [50]). Clarricoats analyzed the traveling-wave ferromagnetic amplifier [51] and Thompson reported on an investigation of spin wave excitation in YIG [52]. Various other aspects of parametric amplification were also studied, such as gain, bandwidth and noise figure [53], circuit aspects [54], electron beam amplifiers [55] and measurements on broad-band amplifiers [56]. Cullen was one of the first to analyze the traveling-wave parametric amplifier [57]. He was able to take into account a number of factors influencing the performance of amplifiers, such as ohmic losses and saturation phenomenon [58], and deduced the consequential maximum gain.

The commercial success of parametric devices at upper microwave frequencies—apart from, possibly, parametric beam devices—depends largely on successful development of parametric diodes with cutoff frequencies in the region of 500 Gc. Thus, for example, efficient harmonic generation in the millimetric band is not possible with presently available diodes because of the proximity of cutoff. On the other hand, it is in the upper millimetric band that microwave tubes are also inefficient and, therefore, diodes as harmonic sources might yet succeed.

A different approach to harmonic generation has been reported by Froome. He obtained good harmonic yield using the nonlinear voltage current and relationship of a mercury arc [59]. Subsequently a somewhat different structure was investigated. Using tungsten anode and calcium cathode in argon atmosphere, Froome was successful in obtaining frequencies in the region of 300 Gc (most recent reports state that nearly 600 Gc were produced) from a source of 35 Gc [60]. The efficiency at present is low (it still compares favorably with any other source available at present), but further work is proceeding.

One of the many reasons why interest in parametric amplifiers is so great and is sustained is because of the very low noise figure realizable with such devices. In this respect, however, masers (despite their greater complexity) have an overwhelming advantage; yet the choice depends on the particular application envisaged [61].

General review articles concerning masers have appeared (*e.g.*, [62], [63]). The activity can be divided into 1) investigation of materials and modes of operation, 2) two level devices, 3) three level devices and applications, 4) ammonia maser oscillators, 5) traveling wave masers, 6) optical and infrared masers.

Although from a scientific point of view masers are a great success, any great commercial success is intimately related to the development of more suitable materials—materials with smaller losses and more favorable relaxation times, materials for operation at elevated temperatures (say 60°K), materials suitable for operation in millimetric band, etc.

Solid-state masers using materials with suitably diluted paramagnetic ions are of chief interest. Of these materials, those containing Cr ions dissolved in Al_2O_3, $K_3Fe(CN)_6$, TiO_2, etc., are preferred. A number of investigators have carried out studies of relaxation phenomena (*e.g.* [64], [65]), while rutile was investigated by Thorp for operation in the millimetric band [66]. Two-level masers are also of interest in the study of properties of paramagnetic ions in a host crystal lattice [67].

A number of engineered versions of masers, mainly for operation at lower microwave frequencies, have been described [68]–[70]. Ditchfield reported on an *X*-band maser operating at 77°K; this is a significant step forward, but, of course, at the expense of efficiency [71]. He also reported one study of variation of relaxation times with temperature.

Cavity masers are substantially (but not necessarily so) narrow-band amplifiers of negative resistance type. For many applications this is a limitation. For this reason there is a wide interest in traveling-wave masers because such amplifiers are reputed to be free from such disadvantages [62], [72]. The preferred construction employs a comb slow-wave structure with ruby as the active material.

The power output of ammonia masers is rather small and the bandwidth very narrow. For this reason such devices are not likely to be used as amplifiers. As an oscillator, the ammonia maser is characterized by a high-frequency stability. The prospect of ammonic maser oscillator as a frequency standard is, therefore, good and at least in one research establishment work is proceeding in that direction [73]. The ultimate frequency stability may probably be of the order of a few parts in 10^{11}.

There are many more fields of interest to those engaged on microwaves: experiments with plasma, cyclotron resonance, etc. The published information is scarce however and largely confined to review articles. Infrared and optical masers, however, ought to be mentioned [74] because of the large impact such devices are likely to have on our future developments.

Utilization

Apart from a number of industrial applications for a variety of uses [3] and applications in defense projects, microwave links remain the chief consumer of microwave equipment.

There is, however, a widespread interest in communication with and *via* satellites; this is evidenced by the large number of lectures and public talks on the subject. The chief effort in this direction seems to be made in the United States; understandably so, because means for putting satellites in space are not, at present, at the disposal of European countries, except, of course, Russia.

In Britain the activity in satellite communication is largely confined to considerations of electronic equipment, investigations of upper atmopshere and theoretical assessments of future prospects; the published information, however, is very scarce.

There is active interest in long-distance communication by waveguide. In fact it transpires that Great Britain, Japan, Russia and the United States are the four countries where research in this field is taking place on a large scale. But, there is interest in a number of other countries, notably France and Germany.

Progress in the field of long-distance communication by waveguide can be gathered from an article by Karbowiak and Solymar [75]. It appears that for efficient operation a waveguide communication system must utilize frequencies corresponding to the upper millimetric band. The authors also point out that the use of special waveguides—either of the dielectric coated variety or a helical construction—is, from a practical point of view, a necessity. It is also stressed that modulation methods such as PCM, where signals can be regenerated at repeaters spaced about 20 miles is also a necessity, but that PCM is not the only possible choice and, furthermore, for short-haul applications a variety of modulation methods could be used with success.

An incidental application of helical waveguides to the construction of high-Q wavemeters has been suggested by Barlow, *et al.* [76]. In this way the authors propose to overcome harmful interference from other modes and thereby improve the wavemeter performance.

Future Trends and Conclusions

The field of microwaves is now so immense that one approaches the task of a critical review with a certain amount of diffidence. It is difficult, indeed impossible, to read and listen to everything that concerns microwaves and yet give a critical account of the work done even though the work concerns a period of time as short as one year. A great deal of preliminary selection has been carried out and it is therefore possible that someone's important contribution has been overlooked.[5] The material has been selected, and the space devoted to the review adjusted, in the following order: new or controversial matters, work of fundamental character or one that is likely to have a significant impact on future developments, miscellaneous fascinating discoveries and modifications. Fields which have not been included in the review (with some exceptions) are: antennas, propagation and microwave tubes. Whereas most of the space was devoted to the theory of microwaves and waveguides, various component measurements and solid-state devices occupy the remainder of the review. Utilization has also been briefly summarized.

In assessing the future trends, it is important to observe that most of the progress achieved in the microwave field is a direct result of research work. Thus future activity and trends will be, in a way, a reflection of the attitude towards research prevailing throughout the country; the more we are research-minded the greater are likely to be the fruits. It is the attitude of mind that determines the future. Admittedly, research is an expensive business, but some years ago the attitude towards research was such as to justify the saying that research is yet another form of hobby.

While not disparaging the spirit behind such an attitude, the reviewer welcomes the change which has taken place during recent years. For it is only by recognizing that research is an essential part of industrial, and indeed of national activity, that a rapid progress in new fields can possibly be made.

Which fields should be exploited first in order that the harvest be worthwhile? This is the big question asked over and over again by many. The simple answer is that in the majority of cases there can be no answer on the available evidence. In fact, it is wrong to ask such a question; for, what is worthwhile?

It is evident from the large volume of published articles and lectures on research management that there is a growing concern (see, for example, [77]) about most aspects of research. It would appear, however, that the surest way to success in research, if that is the aim, is faith. Faith of one member of a research team in another, faith in our profession, and faith in our aims. There is, really, no other recipe. While nowadays, a lot of fine work is still being done by individual people, research is yet another form of social intercourse, but of a very specialized nature.

It is then the research scientists and engineers themselves that have the right qualifications, training and education to guide and influence the future of research.

[5] In such cases the reviewer would be grateful if his attention were drawn to the fact, so that the contribution could be taken into account at a later date.

Yet, so few of them are in sufficiently senior positions to undertake this duty. In this connection Lord Wolton's words spoken in the House of Lords debate on November 21, 1956, may be recalled without comment:

> If industry wants to get first-class scientists and engineers into its service, it has to make perfectly clear to the scientist what can happen to him in the future. The scientist does not want to stay in the laboratory all his days, and just to give advice. He wants to get into a position in which, equally with the finance director or sales director, he will be able in the board room to influence the policy of the business.

Having now established that any future forecast of research progress is next to impossible, we can now summarize the future trends in the microwave field as follows.

There is an indication that in the next few years the fundamental standards of physics will be reviewed; microwaves will play an important part in it.

There is already a greater understanding of theory of electromagnetic fields, and an even deeper understanding of guided waves in waveguides of arbitrary structure should follow. More and more powerful mathematical techniques (such as the Wiener-Hopf technique) are being applied to the solution of waveguide problems. We should, therefore, witness a solution to many outstanding problems.

Microwave techniques are also developing, but there is a general tendency towards higher and higher frequencies. New developments in the upper millimetric band are anticipated and some of the engineering problems connected with the exploitation of the submillimetric spectrum should be overcome.

Efficient generation of coherent radiation in the millimetric and submillimetric spectra is an outstanding problem whose solution will probably lie in the invention of suitable solid-state devices. We may even witness the closing of the present gap between submillimetric and infrared spectra.

In utilization, the application of microwaves to communication systems will dominate our activity (excepting defense projects). In this connection, satellite communication seems to have captured the imagination of many, chiefly because satellites will be launched and rocket research will proceed irrespectively of any other uses, and also because the problems are fascinating and there is a great deal to learn. The commerical success, however. is at present doubtful, but in the infrared or the visible spectrum the chances are perhaps better.

Long distance communication by waveguide will become a reality in a not-too-distant future, particularly since the engineering in the upper millimetric band has reached, now, a high degree of development.

While on the subject of communication systems, it should be observed that although telephone traffic continues to increase, other uses (such as television, data transmission, etc.) which the communication systems serve, increase even faster. It may be that in the years to come telephone traffic will form but an insignificantly small proportion of the activity in communication systems and we will have established even better ways, not yet conceived, of exchanging our ideas.

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