Hyper-Frequency Wave Guides—General Considerations and Experimental Results *

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A peculiar form of electrical propagation is described below. It makes use of extremely high frequencies—even beyond those generally employed in radio. In some respects it resembles ordinary wire transmission but unlike the latter there are no return conductors, at least of the usual kind.

In this transmission, electromagnetic waves are sent through guides made up either of an insulator alone or of an insulator surrounded by a conductor. In a special case this insulator may be air. There are at least four different types of waves or electrical configurations that may be propagated. One of them is such that theory indicates its attenuation through a hollow conductor continuously decreases with increase of frequency. Although the paper deals largely with the nature of this transmission, some of the fundamental pieces of apparatus used in experimental work are described. They include generators, receivers and wave-meters.

INTRODUCTION

THIS paper describes a novel form of electrical propagation by means of which extremely high-frequency waves may be transmitted from one point to another, through specially constructed wave guides. The guide used for this purpose may take any one of several different forms. It may be a hollow copper pipe, which for the higher frequencies now available would be about 3 or 4 inches in diameter, or possibly a somewhat smaller conducting tube filled with some insulating material combining high dielectric constant and low loss, or it may conceivably be a rod or wire of dielectric material.[1]

The phenomena involved in this form of transmission are exceedingly interesting and at first sight paradoxical for in some cases transmission is effected through a single wire of insulating material surrounded by metal in place of a pair of metal wires surrounded by insulation. In others the wire is made entirely of insulating material. In still others electrical effects are observed only on the interior of hollow metal cavities instead of the exterior only as is ordinarily experienced. In all cases there is no return current path, at least of the kind that is commonly assumed in ordinary transmission.

The frequencies appropriate for this form of transmission begin at the higher of those generally known as ultra-high frequencies that is, 2000 mc. ($\lambda = 15$ cm.) and extend to an indefinite upper limit possibly

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[1] The mathematical theory of these phenomena is given in a companion paper by J. R. Carson, S. P. Mead and S. A. Schelkunoff, this issue of the *Bell System Technical Journal*.

set by the properties of available materials. These have for convenience been called hyper-frequencies. When these electromagnetic waves are propagated through either of the two forms of guide mentioned above that incorporates a metal sheath, there is little or no external field and consequently little or no interference from static or other extraneous noises.

As already mentioned there is no return conductor, at least of the kind with which we are generally familiar in ordinary wire or coaxial cable transmission. Corresponding to this difference in physical structure there are striking differences in the character of the waves propagated. On the other hand, when we compare this transmission with radio, where there might at first sight appear to be great similarity, we find little or no correspondence, for it turns out that as regards both the velocity of propagation and attenuation per unit length, radio and wave guides follow quite different laws.

In answer to the natural question as to what practical use there may be for transmission methods of this type the following considerations may be of interest: The size of structure that may be used as a guide is directly proportional to the wave-length. It happens that in structures that are at all convenient in size, the necessary frequencies correspond approximately to the highest range now being tried out in radio. If the size of structure is further reduced to make it more economical for use for long distance transmission, it is then necessary to use frequencies above this range. Thus far these can be produced and handled only with serious difficulty. Although it is possible to reduce the size of the guiding structure for a given frequency by the use of a suitable dielectric we are met with a conflicting difficulty of producing at reasonable cost the necessary medium that will incorporate high dielectric constant with sufficiently low losses. The situation then is that the art at these extreme frequencies is not yet at a point which permits a satisfactory evaluation of practical use. However, for short distance transmission or for use as antennas or projectors of radio waves or for selective elements analogous in nature to the tuning elements so commonly used in radio, there are not the same economic conditions limiting the size of structure. For such uses, then, structures of this type deserve serious consideration.

Theory indicates that one of the four types of waves (designated below as H_0) has progressively less attenuation as its frequency is increased. It happens, however, that this type requires for a given guide a higher range of frequencies than any others. This puts it, therefore, in a frequency range where the art is even less developed than for the other types of transmission and where it is even more difficult to evaluate the economic and practical problems. This paper will, therefore, confine itself to a discussion of some of the fundamental properties of wave guides derived either from calculation or experiment. These properties include characteristic impedance, attenuation and velocity of propagation as well as frequency, selectivity and radiation.

Nature and Properties of Wave Guides

Analysis has shown that there are many kinds of waves that may be propagated through cylindrical guides. However, four of them are of unusual interest and are such as merit special consideration at this time. All four have been experimented with in our laboratory and their more important characteristics have been determined. This experimental work has been paralleled by a mathematical theory [1] to which it conforms most satisfactorily.

A good mental picture of the nature of the waves propagated through guides can probably best be had by abandoning the ordinary concept of current electricity flowing in a "go and return" circuit in favor of that of lines of electric and magnetic force. This latter concept has, of course, always been applicable even for low-frequency transmission over parallel wires or coaxial conductors but due to its complexity in pictorial representation it has usually been avoided. In the form of transmission with which we are now concerned, the field point of view is almost necessary.

Figure 1 is a pictorial representation based on this point of view of the four types of waves mentioned above as found in a guide surrounded by a metallic conductor. In these models the lines of electric force have been represented by solid lines and the lines of magnetic force have been shown by dotted lines. In the longitudinal sections, the small open circles represent lines of force directed toward the observer. The solid circles represent lines directed away from the observer. The designations E_0, E_1, H_0 and H_1 are convenient reminders of certain characteristics of these waves.

The first two waves have been designated as electric because there is a component of electric force in the direction of propagation. For similar reasons the latter have been known as magnetic waves. Such a designation is, of course, rather arbitrary and should not be construed to mean that either component resides alone. It is true here as in other forms of electromagnetic waves with which we are generally familiar, that both the electric and magnetic components are essential to the very existence of the wave and that they may conveniently be considered as different aspects of the same thing.

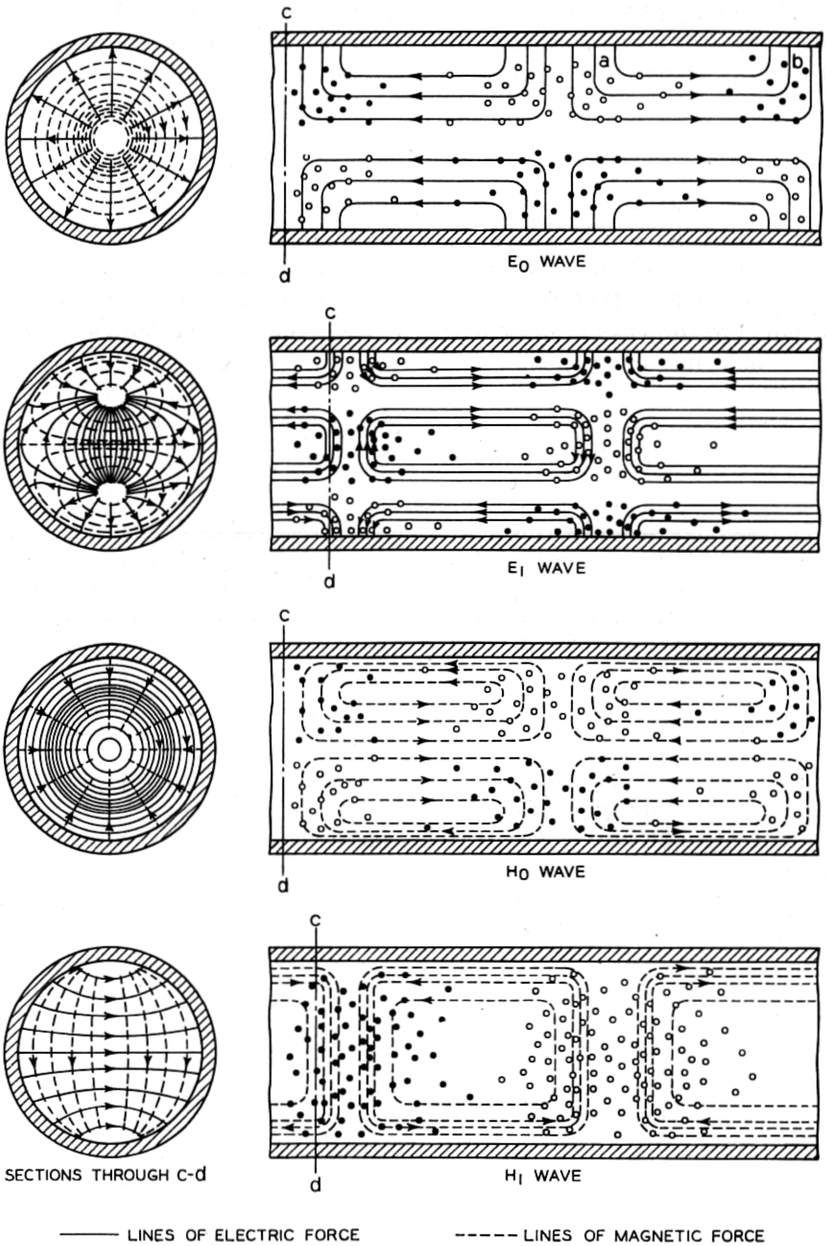


Fig. 1—Approximate configuration of lines of electric and magnetic force in a typical wave guide. Small solid circles represent lines of force directed away from observer. Propagation is assumed to be directed to the right and away from the observer.

Electromagnetic waves cannot be freely transmitted in dielectric wires or hollow conductors at all frequencies but only when the wave-length is less than a certain value set by the material of the guide and its dimensions. There is, therefore, for a given guide a critical frequency below which waves may not be propagated. We refer to this as the cut-off frequency. In a similar way we have for a given frequency, critical or cut-off diameters. These critical frequencies depend not only on the diameter (d) of the guide but on the dielectric constant (κ) of the medium as well. Also they are, in general, different for the different types of waves. For guides enclosed by a metallic conductor the cut-off wave-length is such that the circumference of the guide measured in wave-lengths is equal to the roots of certain Bessel's functions. These in turn result from solution of the Maxwell equations expressed in cylindrical coordinates. These relations are shown more fully in Table I.

TABLE I

Type of Wave	Bessel Functon	Root	Cut-off Wave-length $= \frac{\pi d\sqrt{\kappa}}{X}$
E_0	$J_0(X) = 0$	$X = 2.41$	$1.31d\sqrt{\kappa}$
E_1	$J_1(X) = 0$	$X = 3.83$	$0.82d\sqrt{\kappa}$
H_0	$J_0'(X) = 0$	$X = 3.83$	$0.82d\sqrt{\kappa}$
H_1	$J_1'(X) = 0$	$X = 1.84$	$1.71d\sqrt{\kappa}$

As a simple numerical example let us assume the H_1 type of wave having a frequency of 3000 mc. ($\lambda = 10$ cm.) being propagated in a hollow metallic pipe. The critical diameter turns out to be 5.85 cm. or roughly 2.30 inches. If the space were filled with a material having a dielectric constant of, say 5, this would have been reduced to a diameter of roughly one inch. For higher frequencies or for materials having still higher dielectric constants these critical dimensions would obviously be still further reduced and would be comparable in size to the larger conductors used in ordinary electrical practice. The critical dimensions for the other types of waves are of course larger.

Referring again to Fig. 1 we see that in the so-called E_0 type of wave, a line of electric force originating at a point a on the inner surface of the wall of the guide passes radially toward the center then axially and again radially to a corresponding point b on the inner wall roughly one-half wave-length farther along. The entire wave front as seen in cross section cut through cd consists of a symmetrical arrangement of these radial lines. The magnetic field associated with this wave consists of a series of coaxial circles shown as dotted lines not unlike the magnetic field in a coaxial conductor such as shown in Fig. 2. The E_1 wave consists of electric and magnetic lines very similar in form to those associated with two parallel electric conductors surrounded by a metallic shield. The similarity between the fields for the two dielectric waves and the corresponding two arrangements for ordinary transmission is made more obvious by a comparison of Fig. 1 with Fig. 2. For the most part this similarity ends at this point, however, as their corresponding properties follow quite different laws.

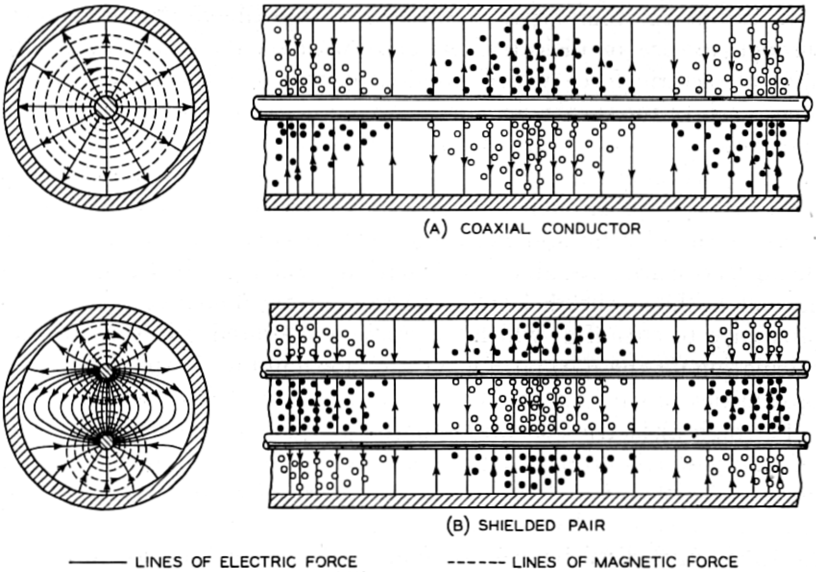


Fig. 2—Approximate configuration of lines of electric and magnetic force in a coaxial conductor and also in a shielded pair of conductors. Note similarity to E_0 and E_1 waves of Fig. 1.

The configurations of the two magnetic waves are somewhat similar to the electric waves provided we assume the electric and magnetic components to be interchanged. Nature has thus far failed to provide us with materials that possess exclusively magnetic conductivity in the sense that copper possesses electrical conductivity so there are no counterparts of Fig. 2 applicable to magnetic waves.

The general shape of the lines of electric force for all of these types of waves have been calculated. These fields have also been verified experimentally by means of a small probe consisting of a crystal detector with short pick-up wires connected to a sensitive meter. This probe was carried over the cross-section of the guide always orienting the detector to obtain maximum deflection. These data confirmed not only the directions of the lines of force but their relative density as well.

There is one characteristic of the H_0 and H_1 configurations that at first sight seems inconsistent with our more usual views of electricity. It is the existence of a substantial tangential component of electric force apparently in close proximity to a metallic conductor. It must be borne in mind however that these frequencies are extremely high and that these distances after all represent an appreciable part of a wave-length.

If any of the four types of waves depicted above are propagated through a wire of dielectric material without the metal enclosure, lines of electric force which previously attached themselves to the inner walls of the sheath, in general, extend into the surrounding space and close as loops. This means that as the wave moves along the guide a portion of the wave power is propagated through the dielectric itself and a part through the surrounding space. The proportionate parts of the electric and magnetic fields resident inside and outside the dielectric are amenable to calculation. As might be expected they depend both on the dielectric constant of the material and on the proximity to cut-off at which the guide is operated. Results of such calculation for the E_0 type of wave are shown in Fig. 3, each for various proximities to cut-off. A dielectric constant of 81 is assumed.

For high dielectric constants and for frequencies far above the cut-off, the power is propagated largely inside the guide whereas for low dielectric constant and for frequencies just above the cut-off, a substantial amount of the power travels outside the guide. In the first case inductive disturbances communicated to neighboring guides are very small and correspondingly the guide is substantially immune to outside disturbances. In the second case these important advantages are absent.

As already stated, many of the properties of wave guides are amenable to calculation. Formulas for the purpose are included in the mathematical paper already referred to. Certain of these properties are intrinsic—as for example, velocity of propagation, attenuation and characteristic impedance. Others may be regarded as extrinsic in that they result largely from the manner in which the guide is used. Examples of the latter are frequency-selectivity and radiation.

Velocity of Propagation

It will be remembered that the velocity of electric waves over ordinary conductors immersed in a particular medium is substantially that of light for that medium. In other words it is equal to the velo-

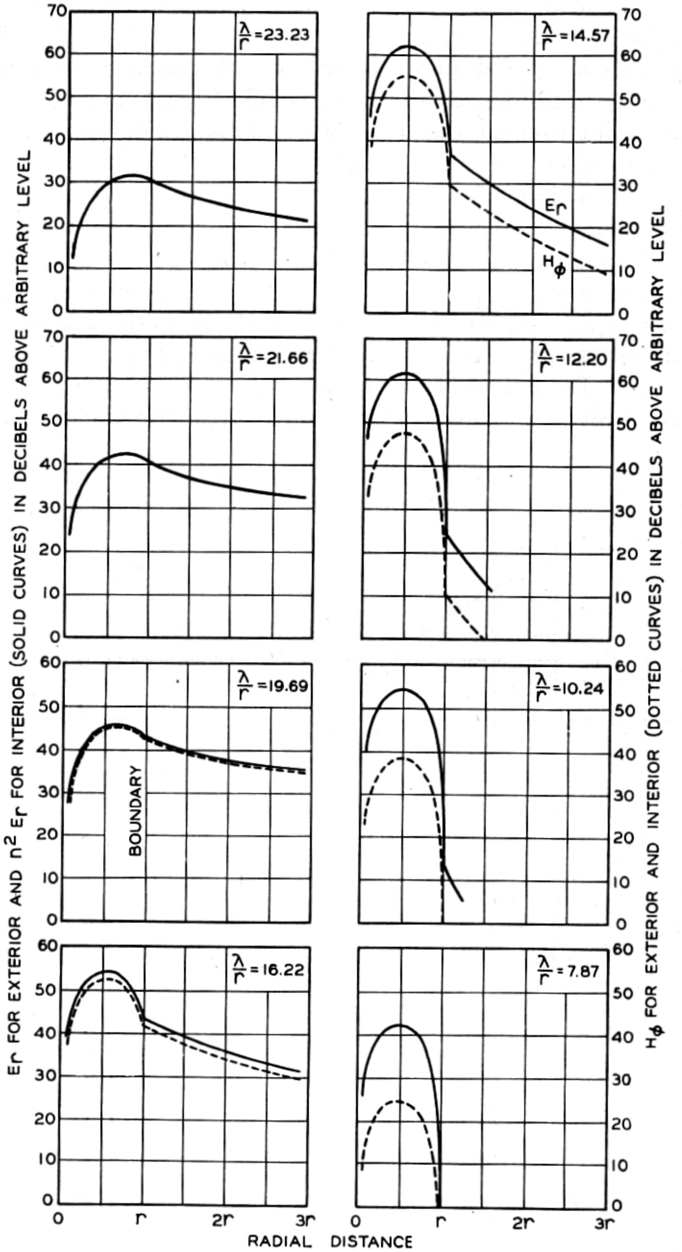


Fig. 3—Relative intensities of electric and magnetic fields inside and outside a dielectric wire while propagating the E_0 type of wave. A dielectric constant of 81 is assumed.

city of light in free space divided by the index of refraction (square root of the dielectric constant). It is also dependent to a small extent on the resistance and permeability of the conductors themselves. The velocity of propagation in wave guides depends not only on these properties but also on the dimensions of the guide as well. For a cylindrical guide it is convenient to express the relation between frequency and dimension as a ratio of wave-length in free space to diameter (λ/d). Also the velocity in the guide may conveniently be expressed as its ratio to the velocity of light ($c/v = k$). Designating by λ the wave-length in free space and by λ_g the wave-length in the guide $k = \lambda/\lambda_g$. Figures 4, 5 and 6 show in graphical form these velocity ratios for three representative cases. The solid curves are calculated. The points are experimental.

Figure 4 covers the case of E_0 waves in a dielectric having a constant

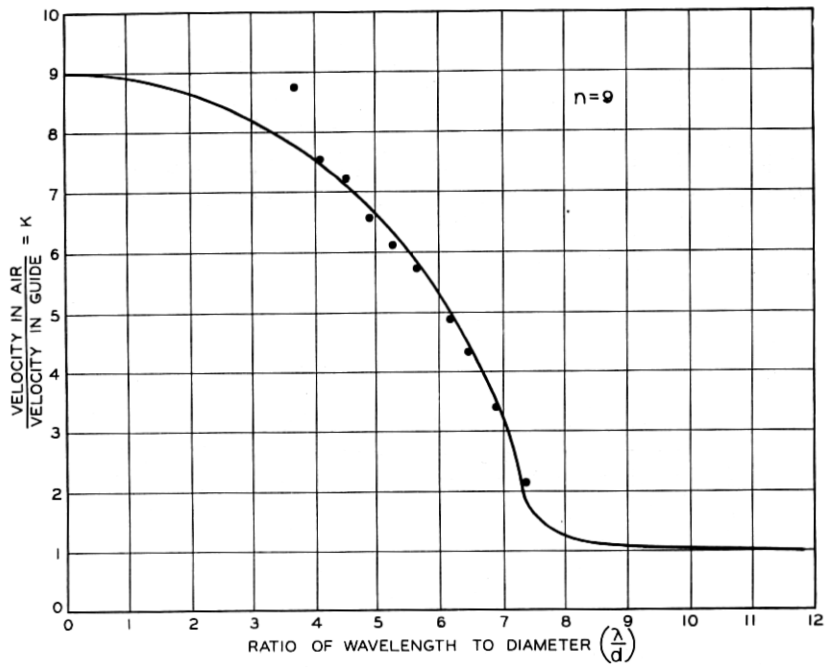


Fig. 4—Velocity ratio for the E_0 type of wave in a dielectric wire ($K = 81$).

of 81 when surrounded by air. It will be observed that at the highest frequencies (lowest values of λ/d) the velocity of propagation is one ninth that of light in free space whereas at the lower frequencies (near cut-off) the velocity is that of light in free space. If the dielectric constant were progressively lowered the velocity even at the highest frequencies would approach that of light in free space and the curve shown would become progressively flatter. In the limit the dielectric constant would be unity and the velocity ratio also would be unity. Under this circumstance the dielectric wire having a constant substantially the same as that of the surrounding medium would cease to function as a guide.

The experimental points of Fig. 4 were obtained by transmitting waves at each of several frequencies ranging from 100 mc. ($\lambda = 300$ cm.) to 400 mc. ($\lambda = 75$ cm.) through columns of moderately pure water. The distances between nodes and loops of the standing waves gave data for the velocity of propagation. The method therefore utilized, in a modified form, a technic sometimes invoked for determining the velocity of electric waves on wires or the velocity of sound in air columns. The columns were supported in thin walled bakelite cylinders each about three feet long. Two diameters were used, 6 inches and 10 inches respectively.

Figure 5 covers the case of the same type of waves and the same

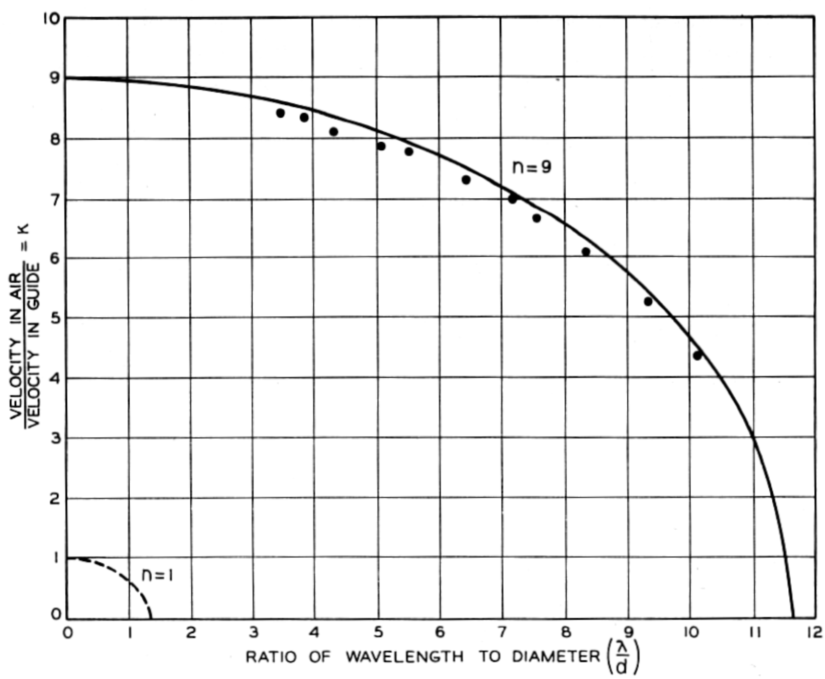


Fig. 5—Velocity ratio for the E_0 type of wave in a metal pipe filled with an insulator ($K = 81$).

dielectric as above but surrounded by metal. It will be noted that the limits of this curve are essentially the same as for the unshielded guide but that the two curves follow rather different courses. If, in this case, the dielectric constant were progressively reduced the curve shown would gradually shrink into the miniature replica shown dotted in the lower left corner. This is of course the practical case of a hollow conductor to be discussed shortly. The above discussion leads naturally to the view that a wave guide is a propagating medium bounded by a dielectric discontinuity. In one case the discontinuity is the interface between the dielectric of the guide and the surrounding medium. In the other it is the interface between the dielectric and a surrounding conductor.

It will be noted from Fig. 5 that at the highest frequencies the phase velocity in shielded guides, like that for unshielded guides, is the same as the velocity along ordinary conductors in that medium but at frequencies near the cut-off this velocity approaches infinity. The solid curve is calculated on the assumption that the medium had a dielectric constant of 81. The indicated points are the results of experiments made with water as a dielectric. For this experiment the water was supported in three-foot cylinders of copper, six inches and ten inches in diameter respectively. The same range of frequencies was used as above. A somewhat closer agreement between calculation and experiment would have resulted if a value of dielectric constant of 78.9 had been assumed in the computations.

TABLE II

VELOCITY RATIOS FOR H_1 WAVES IN HOLLOW CONDUCTORS

Ratio Space Wave-length to Guide Diameter [1]	Ratio Velocity in Free Space to Velocity in Guide		Difference	Per Cent
	Calculated [3]	Measured [2]		
0.980	0.818	0.818	0.000	0.0
1.033	0.795	0.797	0.002	0.3
1.108	0.757	0.762	0.005	0.7
1.246	0.684	0.683	− 0.001	− 0.1
1.375	0.592	0.601	0.009	1.5
1.469	0.510	0.514	0.004	0.8
1.547	0.424	0.429	0.005	1.2

[1] Probable error 0.4 per cent.
[2] Probable error 0.4 per cent.
[3] Probable errors (arising from error in λ/d) range from 0.2 per cent for $\lambda/d = 0.98$ to 1.8 per cent for $\lambda/d = 1.55$. Note that agreement in most cases is within probable error. However the fact that in all but one observation differences have same sign suggests some systematic relation.

Figure 6 is based on calculations covering the case of a hollow conductor (air dielectric) propagating the H_1 type of wave. The experimental data for plotting points on Fig. 6 were obtained at frequencies extending from 1500 mc. ($\lambda = 20$ cm.) to 2000 mc. ($\lambda = 15$ cm.) on hollow cylinders ranging in diameter from four inches to six inches. Relative velocity was determined from the length of standing waves set up in short sections of these wave guides. The measurements represented were made with much more refined apparatus than utilized in obtaining the data for Figs. 4 and 5.

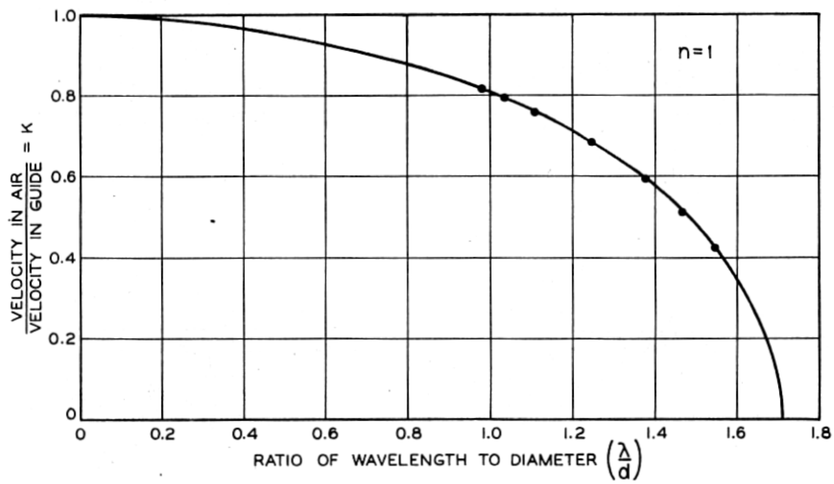


Fig. 6—Velocity ratio for the H_1 type of wave in a hollow metal pipe.

Attenuation

Figure 7 shows in graphical form the calculated attenuations suffered by each of the four more common types of waves when traveling through a hollow copper pipe 5 inches in diameter. It is immediately obvious that the attenuation is infinite for all waves at their respective cut-off frequencies. However, at frequencies above the cut-off this attenuation becomes finite, generally descending to values comparable with attenuations experienced on ordinary conductors at considerably lower frequencies. For the E_0 and E_1 types of waves the attenuation falls from infinity at cut-off to a minimum at a frequency $\sqrt{3}$ times the cut-off frequency after which it again begins to increase and ultimately varies in a linear fashion much as does attenuation over ordinary conductors. For the H_1 type of wave this minimum comes at a frequency 3.15 $\sqrt{3}$ times the cut-off frequency. Thus we see that for these three types, wave guides are somewhat similar in their behavior to ordinary conductors when operated at the highest frequencies but they depart radically at frequencies near cut-off.

Calculations indicate that the H_0 type of wave has a descending attenuation characteristic at all frequencies above cut-off. This suggests that we may be able to realize very low attenuation merely

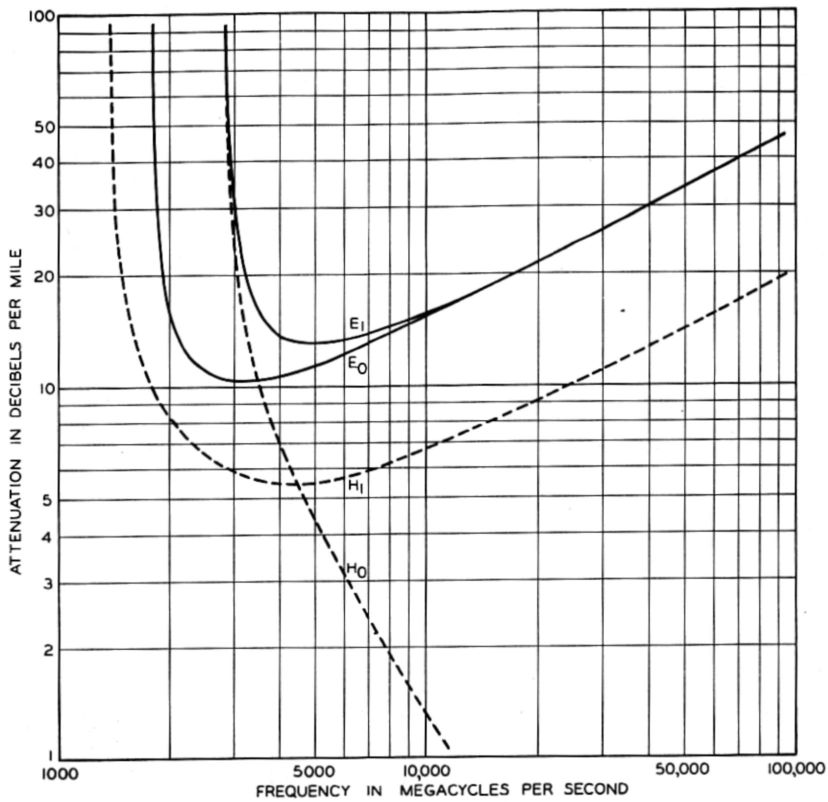


Fig. 7—Attenuations suffered by each of the more common types of waves in a hollow copper pipe 5 inches in diameter.

by raising frequency. This remarkable property is, so far as the author is aware, altogether unique in the realm of electrical transmission. It should be borne in mind, however, that for structures having reasonable dimensions, these low attenuations can only be obtained from frequencies that are above those now readily available. It may be noted in passing that at the minimum of the H_1 curve, transmission is flat to a half db per mile over a band-width of 4000 mc.

The author's experimental work on attenuation is still incomplete, but the results to date are altogether in keeping with calculation. Work done at or near cut-off for all four types of waves confirms their descending characteristics at these points. Other more systematic measurements made on the H_1 type of wave over a considerable range of frequencies are also in good agreement with calculation. Typical results are shown in Fig. 8. They were made on a straight section of

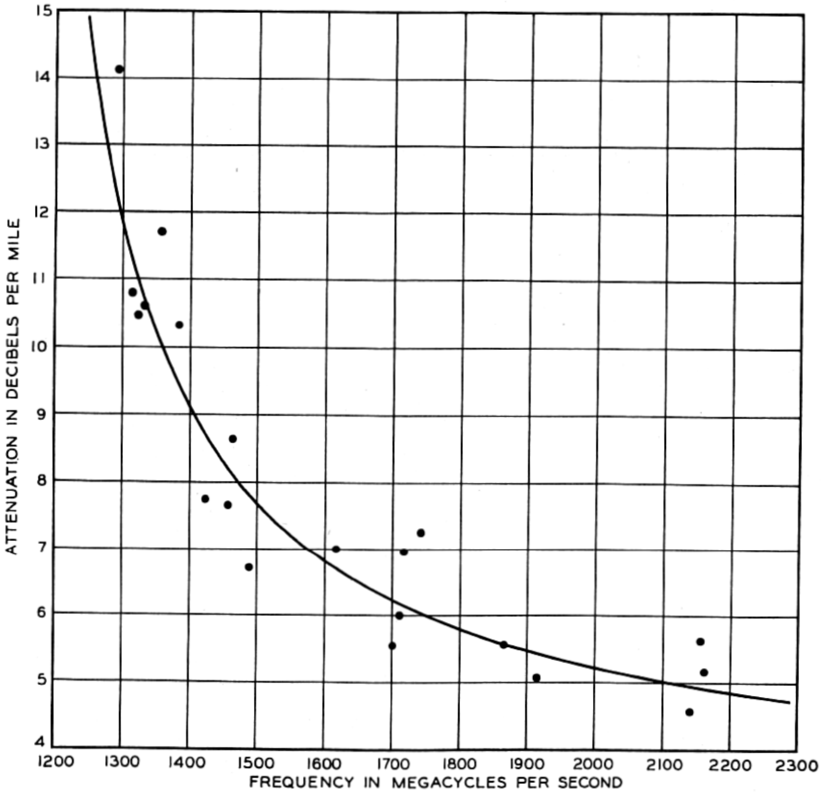


Fig. 8—Attenuation suffered by H_1 waves in a 6-inch hollow copper pipe. Curve is calculated. Plotted points are experimental.

hollow copper pipe six inches in diameter and 1250 feet long. No experimental attenuation data on the H_0 type of wave are yet available except at cut-off. It may be argued, however, that the same theory applies to all four forms of waves so that data tending to confirm the calculated attenuation of one form of wave tends also to substantiate the predicted attenuation for the other forms as well.

Characteristic Impedance

A second intrinsic property of wave guides is characteristic impedance. It may be calculated by integrating the complex Poynting vector over the cross-sectional area and dividing the result by the square of the effective current. Formulas for this purpose are included in the companion mathematical paper referred to above. The numerical results of such calculation are shown in Fig. 9 for a 4-inch diameter hollow copper conductor for each of the four principal waves mentioned above.

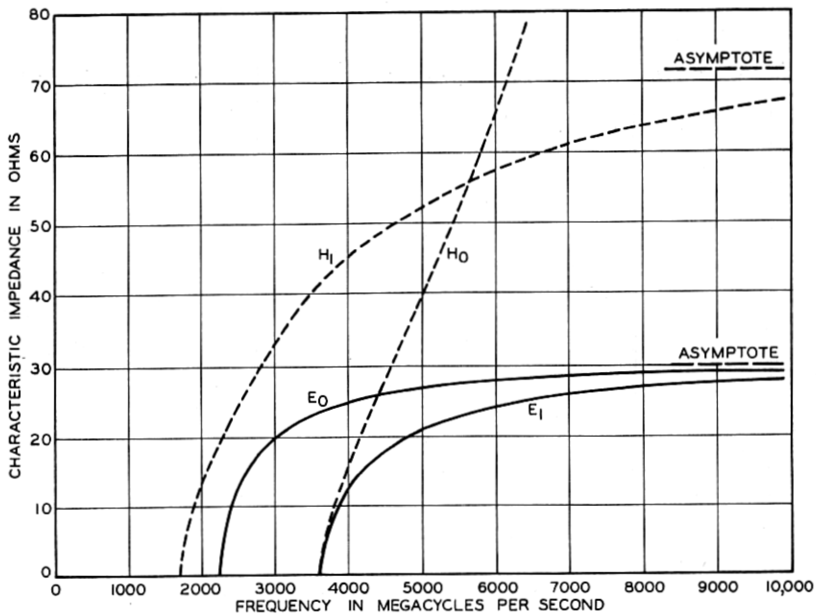


Fig. 9—Calculated values of characteristic impedance of a 4-inch hollow copper pipe for each of the four more common forms of waves.

It will be remembered that when an ordinary wire line is terminated in its own characteristic impedance there are no standing waves. This condition leads to a maximum of power delivered to the receiver. Such an impedance match is sometimes referred to simply as a termination. Terminations for wave guides are entirely similar in their behavior to those of wire lines and may be had by a variety of means. One is a thin film of resistance material placed perpendicular to the axis of the guide followed at a prescribed distance by a perfectly conducting reflector. It is often convenient to provide the latter in the form of a movable piston. Another form is a resonant chamber containing some dissipative material. Conditions for termination may be calculated in so far as the properties of materials are known or they may be determined experimentally by successive adjustments of film density and piston adjustments until standing waves have been eliminated. Figure 10 shows graphically a typical series of experi-

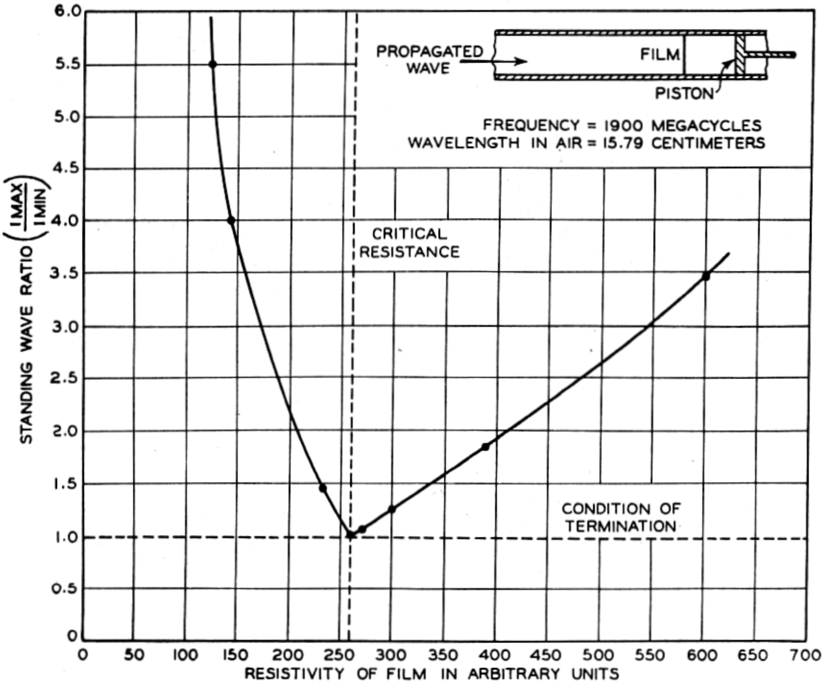


Fig. 10—Typical set of experimental data as various degrees of impedance match are obtained.

mental data of the magnitudes of standing waves as various degrees of impedance match are obtained.

Frequency Selectivity

It is evident from Fig. 7 above that wave guides are inherently high-pass filters. There is still another property of a wave guide that may also provide selectivity. It depends on the principle of standing waves. By this means, resonance effects may be produced that make a short section of guide behave somewhat as if it were a simple series circuit consisting of an inductance and a capacity in series with an electromotive force. Under other conditions, it may behave as a circuit made up of inductance and capacity in parallel with an electromotive force.[2] At still other frequencies it may present to a source a positive (inductive) reactance or a negative (capacitive) reactance. This makes possible circuit elements which may be combined to form various filter or network equivalents. We may have, therefore, from wave guides frequency selection by either or both of two fundamentally different properties.

Radiation

Discontinuities in wave guides, particularly those in which no shield is present, tend toward losses by radiation. In the case of a hollow conducting pipe radiation issues from the open end much the same as sound waves from a hollow tube. It has been possible to expand the ends of these pipes into horns, thereby obtaining effects very similar to those common in acoustics. Such an electrical horn not only possesses considerable directivity but it may also provide a moderately good termination for the pipe to which it is connected. In so doing its function is probably quite analogous to that of a true acoustic horn which provides an efficient radiating load for its sound motor.

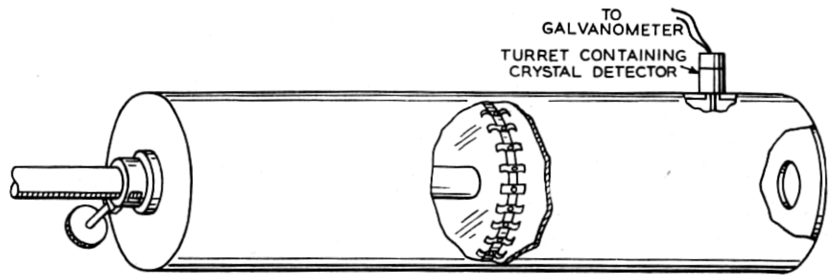
Some Apparatus and Methods Used in Wave Guide Studies

It is obvious, of course, from the very nature of guided waves that the apparatus and methods must be rather different from the more common electrical methods. This difference is such that an adequate description would require more space than is here available. However, for purposes of completeness a few of the more interesting and fundamental aspects of the experimental side are included below. For the most part this description will center around the H_1 type of wave. (See Fig. 1 above.)

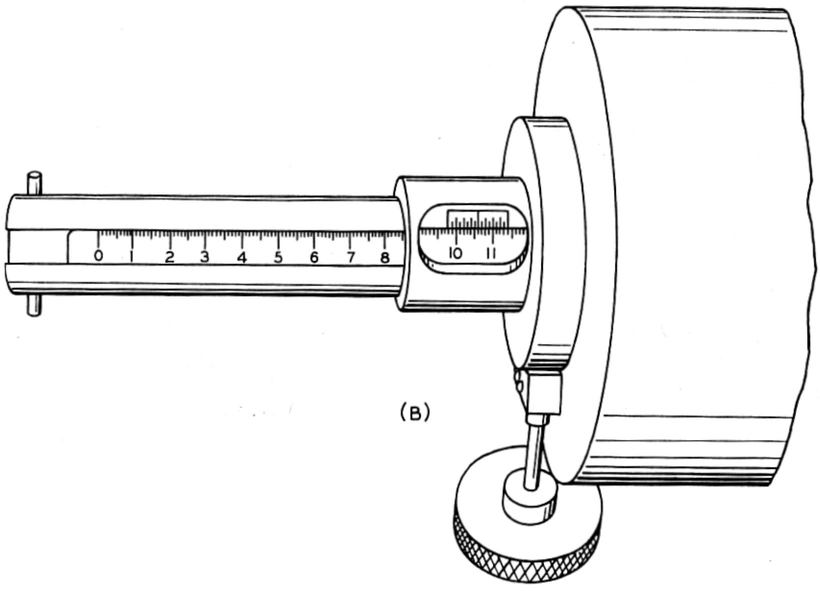
The Simple Resonant Chamber

In much the same way that the simple tuned circuit containing localized inductance and capacity is fundamental to the radio art so also is the simple resonant cavity fundamental to wave guide work. Although it may assume a variety of forms, one of the more obvious is a short piece of cylindrical wave guide, preferably of hollow metal pipe bounded by a piston and an iris diaphragm as shown in Fig. 11.

[2] In pursuing this work it has been convenient at times to refer not only to *circuit* analogues but also to *optical* and also *acoustical* analogues. This has been due in part to the lack as yet of an adequate vocabulary and in part to the hybrid nature of the subject at hand.



(A)



(B)

Fig. 11—A tunable chamber resonant to short electric waves.

In its role as a tuned circuit, the resonant chamber is sometimes used as a wave-meter, sometimes in connection with a generator of short waves (thereby enabling a vacum tube to work more effectively) and sometimes as an element in a receiver (thereby impressing on a detector a maximum of the received wave power). When such a chamber is excited by very short electric waves and is varied in length, resonance takes place at certain specified intervals depending on the frequency and phase velocity. This condition may be detected either by a crystal detector and meter located just outside of the iris opening or by a somewhat more elaborate arrangement whereby a crystal mounted in a shielded cartridge is coupled to the chamber by a probe wire perhaps a quarter inch long extending through a hole in the wall. Fig. 11*A* shows one form of resonant chamber complete with detector. The piston position is read off on a scale and vernier (Fig. 11*B*). Successive positions at which resonance is noted give data for determining velocity of propagation. Chambers of this kind having various diameters were used to verify the velocity ratios shown earlier in this paper. Electrical connection between piston and walls may be had by numerous phosphor bronze fingers, or perhaps by ball bearings distributed in a race around the periphery. Good contact is not always essential. In fact, fair work may sometimes be done with a loosely fitting piston or even an insulated piston.

Resonant chambers may be activated merely by placing them within a foot or two of a source of waves such as a Barkhausen oscillator. Their dimensions must, of course, conform to the wave-length requirements as outlined above. Standard 5-inch OD brass pipe having one-sixteenth inch wall has been found satisfactory for the frequency range from 1500 mc. ($\lambda = 20$ cm.) to 2000 mc. ($\lambda = 15$ cm.). Any convenient length around 2 feet is appropriate for the variable type of chamber.

Generators

One arrangement for generating the H_1 type of wave consists of connecting the primary source of waves between diametrically opposite points on the inside of a hollow cylindrical conductor as shown by Fig. 12*A*. This primary source may consist of a positive grid (Barkhausen) tube or a magnetron.[3] Both have been used successfully to give frequencies up to about 3330 mc. ($\lambda = 9$ cm.).

A typical arrangement of such an oscillator is shown in Fig. 12*B*. The terminals of the spiral grid of the Barkhausen tube are connected to diametrically opposite points through a suitable by-pass condenser. The filament and plate leads enter along a plane perpendicular to that of the grid. Since the grid leads correspond to lines of electric force in the generated wave, the diametral plane perpendicular thereto corresponds to an equipotential. By locating the plate and filament leads in such an equipotential, their presence will not materially affect the normal field prevailing in the chamber. In the design shown the filament connectors constitute the outside plates of a three-plate by-pass condenser. The third or central plate is a rigid member grounded on the main guide. It connects to the plate of the Barkhausen tube. Connections to the exterior are had through five

[3] "Vacuum Tubes as High-Frequency Oscillators," M. J. Kelly and A. L. Samuel, *B.S.T.J.*, Vol. 14, p. 97, January 1935.

insulated binding posts. The oscillator unit shown carries on its exterior a plug connector leading by cable to a nearby d-c. power supply unit.

If an oscillator similar to that described above were connected into the middle of a long hollow pipe, waves, would of course, be propagated in both directions. Those that would ordinarily be propagated to the left may be reflected by a suitably located reflecting wall or piston so

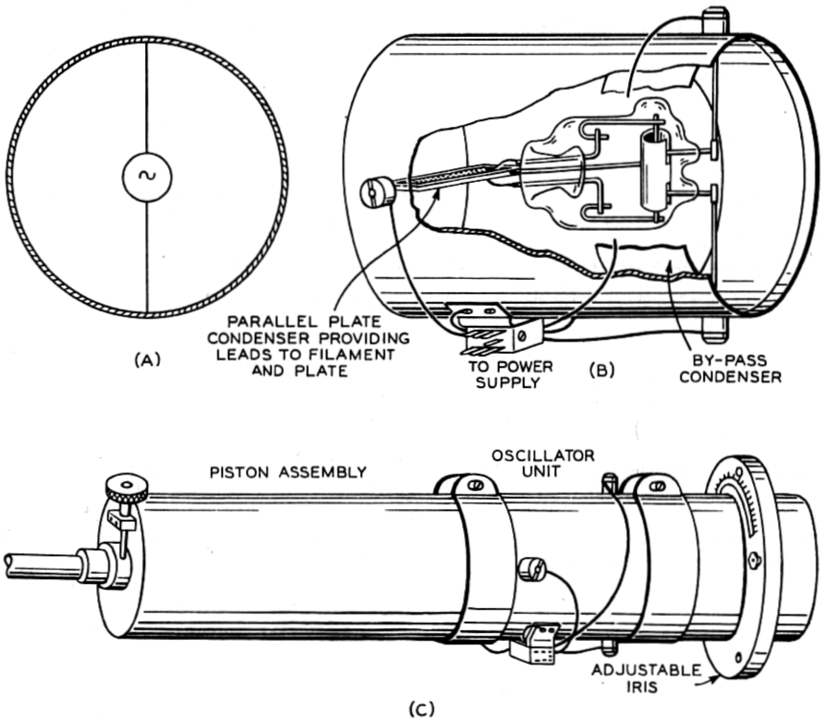


Fig. 12—Various component parts of a wave guide generator. (*A*) Schematic representation. (*B*) The oscillator unit. (*C*) Complete generator including oscillator piston and iris.

as to reinforce those being propagated to the right. Also an iris of suitable proportions may be so located in front of the generator as to further enhance oscillations. As has been pointed out above the section of pipe bounded by the piston and iris together approximate in behavior a tuned circuit. It is convenient to regard the chamber as a load impedance characteristic of the tube itself or perhaps it should more properly be regarded as a transformer by which the oscillator is matched to the line.

In practice the generator may conveniently be built up from an oscillator unit, a piston assembly and an adjustable iris, all of the same diameter of pipe fastened together by exterior metal clamps as shown in Fig. 12*C*. The open end of this generator may be connected to a guide over which transmission is desired or it may be coupled loosely to some nearby laboratory apparatus on which measurements are to be made.

The total length of the chamber and hence the piston setting will of course depend on the frequency to be generated. In general this will be roughly an integral number of half wave-lengths. The relative position of the oscillator along the length of the chamber will depend on its impedance characteristics and to some extent on the diameter of the iris opening. For a piece of laboratory apparatus where frequency variability is desired these various dimensions should preferably be adjustable as shown. If a source of single frequency is desired, the resulting apparatus may be greatly simplified as all of these dimensions may be fixed at the time of construction.

The Tuned Receiver

By reversing the principle used in the generator above, replacing the oscillatory source by a suitable indicator the resonant chamber becomes effectively a simple tuned receiver. If the indicator is appropriately located along the length of the chamber, substantially all of the incident power will be absorbed and the device as a whole will be a veritable sink of wave power. It may be clamped to the end of a long wave guide, thereby constituting a termination, or it may be used to pick up short radio waves of not too small amplitude. See Fig. 13.

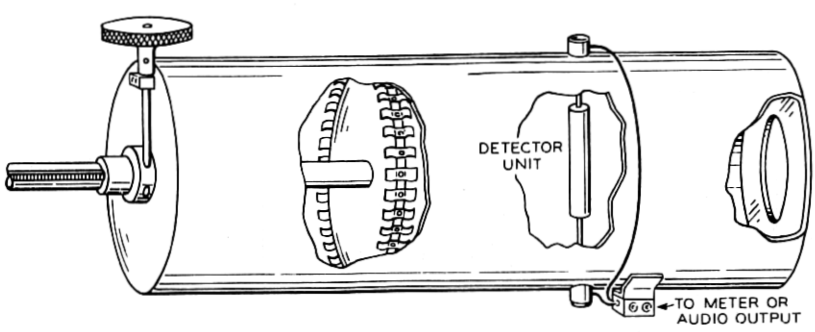


Fig. 13—A tuned receiver based on the resonant cavity principle.

Indicators

It is often desirable to have available in the laboratory some kind of a wave indicator or probe such as shown in Fig. 14. This one consists of a simple silicon detector in cartridge form, together with a microammeter, both mounted on a fibre support of convenient size and shape for exploring the fields prevailing around any piece of apparatus. It is easy to show by this means that there are no appreciable fields prevailing around a generator such as described above except near the orifice. Also this probe may be used to determine the

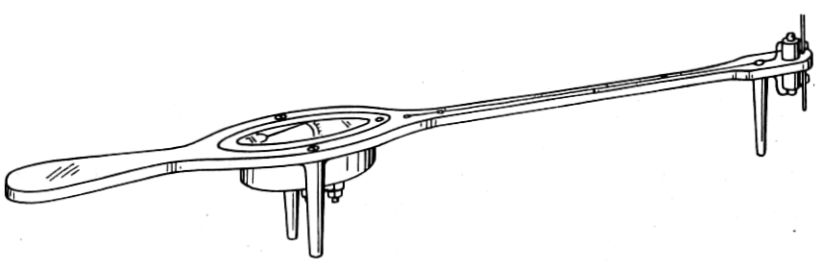


Fig. 14—A convenient probe for exploring the field around a source of waves.

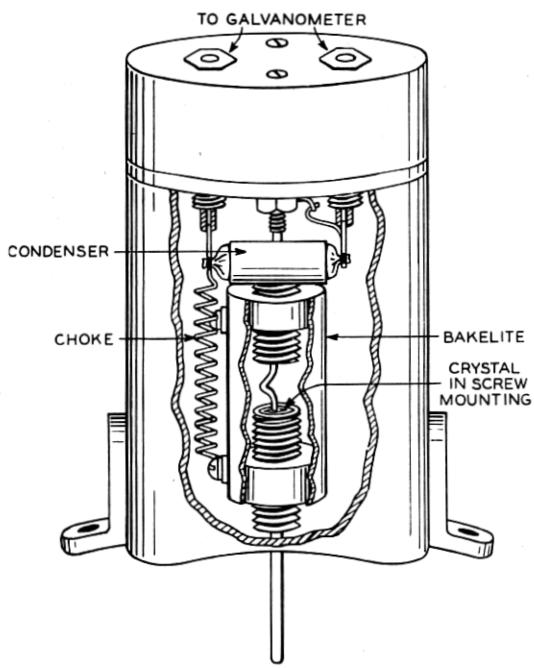


Fig. 15—A detector mounting suitable for indicating the presence of waves in a guide.

approximate orientation of the lines of electric force in the wave front as well as the general directive pattern of the radiation.

Figure 15 shows details of a crystal detector mounting suitable for an indicator on a wave-meter. When silicon crystals are used, units may be had that will hold their calibrations moderately well over considerable periods of time. Thermocouples of both the cross wire and deposited type have been used with moderate success. Also diode and triode rectifiers have been tried. However, for general laboratory use where simplicity and convenience are important the crystal detector is perhaps best.

Wave-Meters

It is, of course, desirable in this work to know the frequency or wave-length being used. The simple resonant chamber already described enables wave-length to be measured accurately. However, such a device does not give directly the wave-length in free space since in these chambers phase velocities are in general greater than ordinary light. It is true, of course, that a suitable conversion curve can be prepared. However, it is often more convenient to use for a wave-meter some form of a coaxial conductor system on which standing waves may be measured. These will be very nearly at least the length of the corresponding waves in free space.

Figure 16 shows a wave-meter based on this principle. The conductor (*a*) and the hollow cylinder (*b*) constitute the coaxial conductors. A bridge (*c*) in the form of a conducting disc is made movable by means of the threaded tube (*d*) which passes over the central conductor (*a*). This tube carries a millimeter thread engaged by the knurled head (*e*). One complete turn of this head therefore raises or lowers the bridge by one millimeter. If coarse adjustments are desired the head may be disengaged from the threaded tube by a cam operated by the knob (*f*), and the tube raised or lowered by taking hold of its extended portion. The outer conductor or shell carries an open slot (*g*) through which an index (*h*) attached to the shorting bridge (*c*) extends. This index passes over a centimeter scale (*i*). The outer conductor is mounted on a short piece of wave guide so that the apparatus may be clamped in line with other apparatus. The inner conductor (*a*) extends through a small opening in the section of wave guide far enough to extract from the passing waves enough power for activating the wave-meter. This coupling may be varied as needed by extending or retracting a third small rod (*jj'*) running through the center of central conductor (*a*).

Resonance is indicated by a crystal detector (*k*) and d-c. meter. This detector is only loosely coupled to the coaxial system by a small

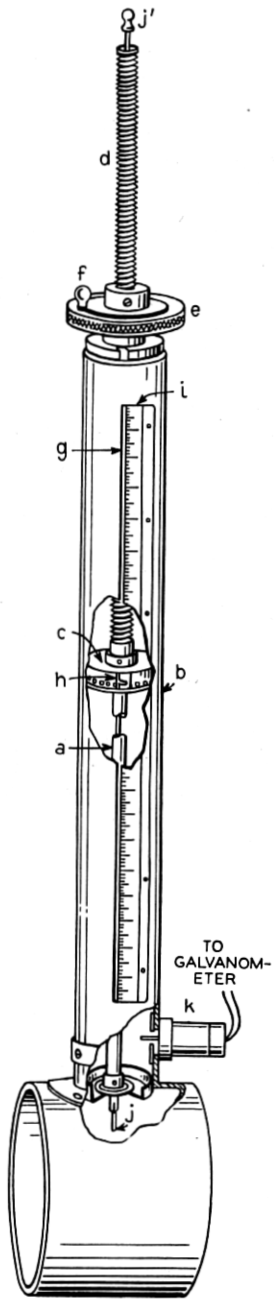


Fig. 16—A form of coaxial conductor wave-meter particularly adaptable to wave guide work.

pick-up wire extending through the walls of the hollow cylinder. This form of wave-meter is moderately fast and permits wave-length differences of one or two hundredths of a centimeter to be readily detected.

Miscellaneous Apparatus

Sometimes it is desirable to change the length of a pipe without changing its diameter. For this purpose telescoping pipe is to be avoided. A pipe with removable sections may, however, be provided. Units of 10 cm., 5 cm., 2 cm., 2 cm. and 1 cm. have been found convenient. They are aligned in a slightly larger half-section of the same kind of pipe which provides their support.

It may be desirable at times to investigate the field inside a pipe to determine if standing waves are present. This may be done by mounting a detector similar to that shown in Fig. 15, on a carriage so it may be advanced along a slot cut in a piece of wave guide perhaps 60 cm. long. Often it is necessary to pass from one size of pipe to another. A conical reducer perhaps 30 cm. long may be used for this purpose.

It is usually desirable to construct components such as the above with lengths of some integral number of centimeters such as 10 cm., 20 cm. or 50 cm. This obviously facilitates the addition of the component lengths used and often simplifies calculation.

It is obvious from the above that a laboratory working with wave guides must use for its circuit components such unusual electrical items as hollow pipes, movable pistons and iris diaphragms. These should be capable of quick assembly into a variety of forms, sometimes as a generator, sometimes as a tuned receiver and sometimes as a termination. This object imposes a wide range of requirements that can best be met by mounting the parts by means of clamp supports on a saw-horse arrangement or wave guide bench such as shown in Fig. 17.

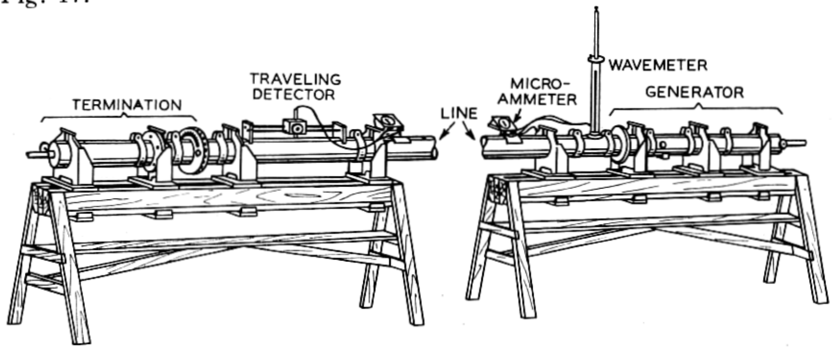


Fig. 17—Bench mountings with typical apparatus used at the transmitting and receiving ends of an experimental wave guide.

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