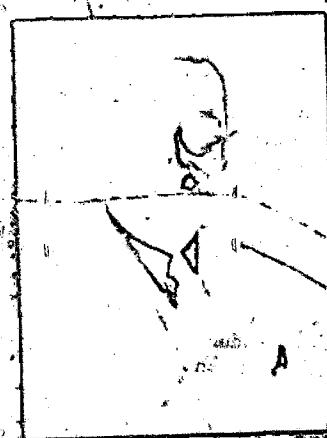


New Experimental Methods

#1583



Applicable to Ultra-Short Waves*

BY G. C. SOUTHWORTH

Bell Telephone Laboratories, Inc.

New York, N. Y.

Introduction

THE principles underlying wave guide transmission, a novel form of electrical transmission for which experimental results were recently reported,¹ appear to offer a new approach to the problem of high frequency electrical measurements. In this form of transmission certain configurations of electric and magnetic force are propagated as waves through cylinders of dielectric. A special case is, of course, that where the dielectric is air. For this case a metal sheath is necessary.² If, however, the dielectric constant is high the sheath may not be altogether essential.

The present paper describes some of the early steps which have been taken at the Bell Telephone Laboratories in the application of these principles to high frequency electric measurements in the hope of extending the range materially beyond the present rather indefinite frontier of about 10^9 cycles per second. The simple hollow pipe, which is perhaps the most convenient form of guide for laboratory use, will be assumed throughout this paper. For this case the diameter must be at least 0.58 wavelength.

One advantage of this new method is that if necessary both the source and the sink of high frequency power may be located entirely within the guiding structure thereby eliminating many of the difficulties incidental to radiation loss and

to the spurious coupling effects that are common in ordinary high frequency work. It also turns out that the resistance losses in the walls of a metal pipe may be made less than the corresponding losses if the waves are propagated over a conventional circuit of either the parallel, or coaxial conductor form. A better understanding of this method may be had by reviewing briefly some of the fundamental properties of wave guide transmission.

Forms of Waves

Theoretically at least, there is an infinite number of wave forms that may be propagated through guides of circular cross section. Each form corresponds to a particular solution of the differential equations appropriate to this problem. Four of these waves are of particular interest and have been made special objects of study in our laboratory; they may be distinguished by the configurations of the lines of electric and magnetic force in which they are comprised. These are shown in Fig. 1.

The first two waves have usually been designated as electric waves because there is a substantial component of electric force in the direction of propagation. For similar reasons the last two have been called magnetic. The subscripts are related to the mathematical expressions for these waves but they are also convenient reminders of their configurations. The experimental methods described below will be confined to the so-called II , wave.

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FIGURE 1.

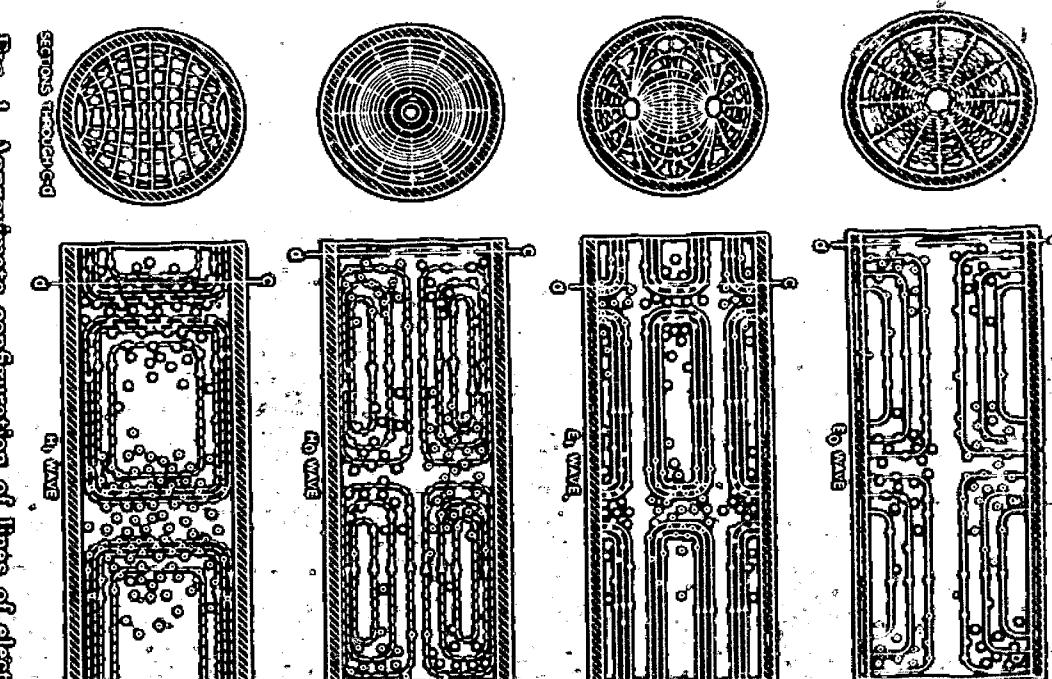


FIG. 1. Approximate configuration of lines of electric and magnetic force in a typical wave guide. Solid lines, lines of electric force; dotted lines, lines of magnetic force; black dots, toward observer; circles, away from observer.

Critical Frequencies

Electromagnetic waves may be freely transmitted in dielectric wires or hollow conductors 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 (ϵ_0) 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 wavelengths is equal to the roots of certain Bessel's functions. These in turn result from

solutions of the Maxwell equations expressed in cylindrical coordinates. These relations are shown more fully in Table I.

Most of our work has been done at frequencies between 2000 $m\epsilon$ ($\lambda=15$ cm), and 6000 $m\epsilon$ ($\lambda=5$ cm). For this range of frequencies the diameters of the guide range from about one to five inches (2.54 cm-12.7 cm). The methods which are described below are, of course, applicable to much higher frequencies such as for instance, the nearly 50,000 $m\epsilon$ reported by Cleeton and Williams.³ It is interesting to note that for this latter frequency ordinary hollow metal wire $\lambda/4$ inside diameter should be sufficient to guide these waves from one point to another.

The critical relations that must be satisfied before power may be propagated makes the wave guide essentially a high pass filter. This is a convenient property for laboratory use. By this means it is possible to reject in a wave guide all frequency components below a certain limit set by its diameter. Also it is sometimes possible to pass certain types of waves and reject others even though they be of the same frequency.

An example of the latter application will perhaps be in order. It was found that in a given source of H_0 waves operating on a wave-length of 15.5 cm there was an extraneous component of the E_0 type. The guide in which experiments were to be conducted was 12.5 cm in diameter and therefore capable of supporting both the wanted and the unwanted components. To obviate the difficulty a short section of pipe was introduced into the connecting line in which the diameter was slowly reduced from 12.5 cm to 10 cm and back to 12.5 cm. This throat was sufficient to suppress the E_0 component without seriously attenuating the desired H_0 curve. It would of course have been even more effective if the experiment itself had been conducted inside of a 10 cm pipe.

Type of Wave	Bessel Function	Root	Cut-off Wave-length
E_0	$J_{1/2} = 0$	$\lambda = 2.41$	1.346 ^a
H_0	$K_{1/2} = 0$	$\lambda = 3.83$	0.826 ^a
H_0	$K_{3/2} = 0$	$\lambda = 1.84$	1.146 ^a

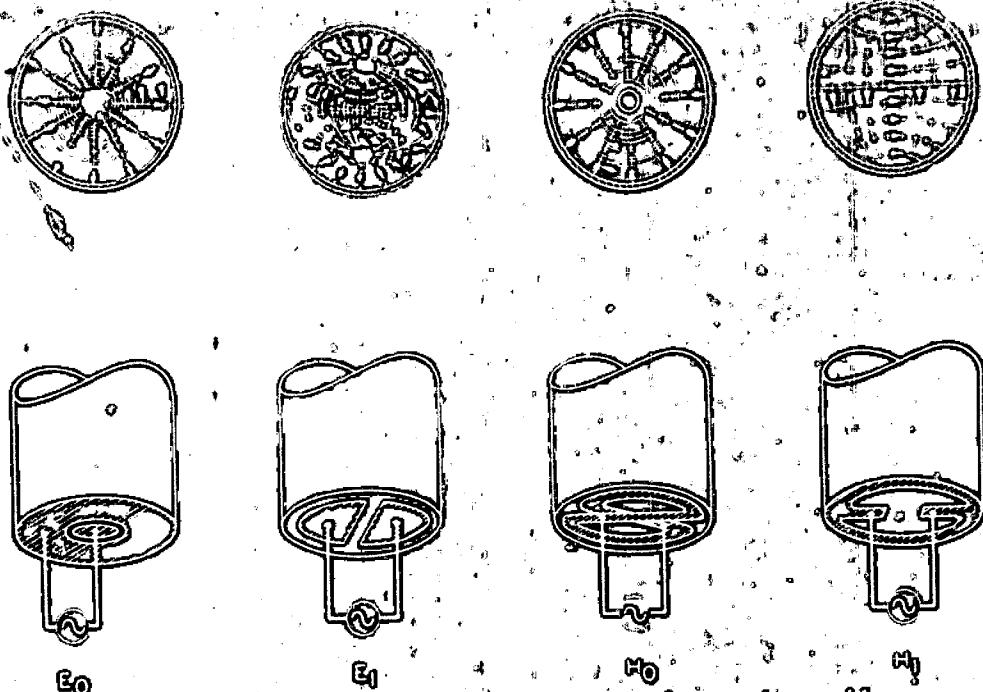


FIG. 2. Methods of launching various types of waves in a guide.

Resonance Effects

Short sections of wave guide may be made to resonate electrically much the same as organ pipes and air columns resonate acoustically. In the electrical case the resonant chamber is somewhat analogous to a tuned circuit consisting of a localized inductance and capacity. It is perhaps even more nearly analogous to a tuned Lecher frame. On account of the fact that both Joulian and radiation losses are low in the resonant chamber its degree of sharpness may be made very high.

In its role as a tuned circuit, the resonant chamber may be used in a variety of ways. It may either be a simple wave meter or a frequency determining unit for an oscillator. Also it may be used as an impedance matching device sometimes in connection with a generator (thereby enabling a vacuum tube to work more effectively) and sometimes as an element in a receiver (thereby impressing on a detector a maximum of received power). It is quite feasible also to use it as a means of impressing wave power on laboratory specimens that may be under investigation.

Generators

Figure 2 shows in a simple schematic way how each of these waves may be launched in a guide. Fig. 3 shows in greater detail how one of these

methods is put into practice when the H_1 wave is desired. The terminals of the spiral grid of the Barkhausen tube are connected to diametrically opposite points on a pipe 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 leads to one filament and the plate 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 remaining filament lead of the Barkhausen tube. Connections to the exterior are had through five 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. Simple coils of wire of perhaps 10 turns each 1 cm diameter may be substituted for the three-plate condenser without any great loss in efficiency.

The Barkhausen oscillator mentioned above is merely typical of the sources that may be used in guides. We have adapted to this work magnetrons such as described by Kilgore⁴ and also negative grid tubes such as described by Samuel.⁵ In the latter case use has been made of both the fundamental and the harmonic power.

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 wall or piston so 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 its together approximate in behavior a tuned circuit. It is convenient to regard the chamber as a load impedance characteristic of the vacuum tube itself or perhaps it may more properly be regarded as a transformer by which the oscillator is matched to the line. Under certain circumstances it is convenient to use the adjustable iris as a means of controlling the output of the oscillator.

In practice the generator may possibly 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. 3 (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, naturally, depend on the frequency to be generated. The relative position

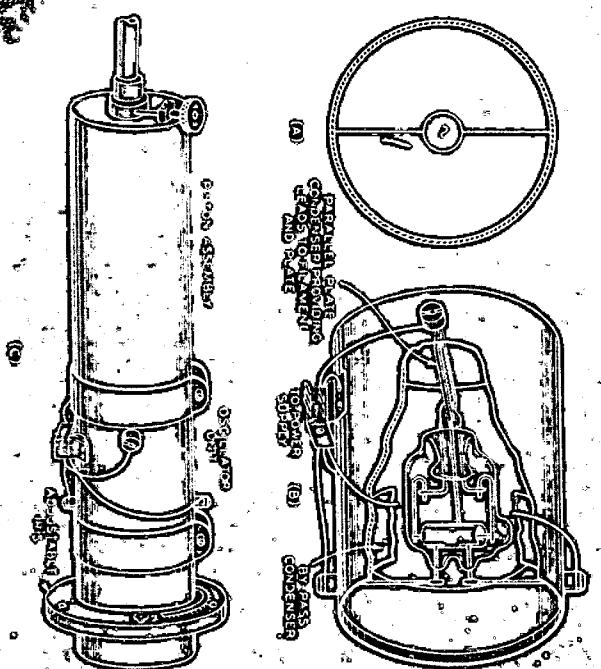


Fig. 3. Various component parts of a wave guide generator: (A) Schematic representation; (B) The oscillator unit; (C) Complete generator including oscillator piston and clamps.

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. However, none of these dimensions is especially critical. 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 detector, the resonant chamber be-

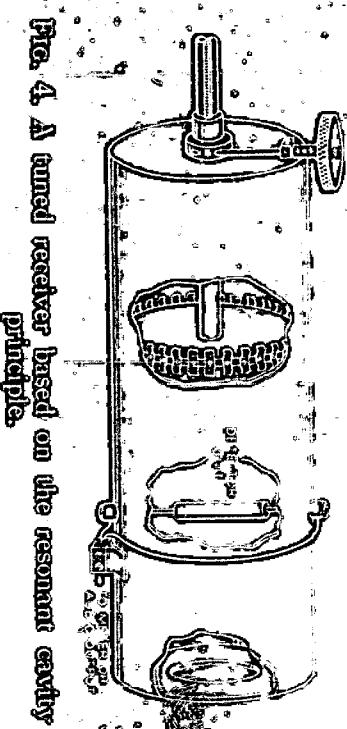


Fig. 4. A tuned receiver based on the resonant cavity principle.

comes effectively a simple tuned receiver. If the detector 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. 4.

In a modification of this tuned receiver in which sharpness of resonance was of greater interest than a maximum of received power, the detector and its mounting were moved to the exterior of the chamber as shown in Fig. 5. Only enough of the residual power was abstracted to operate the indicating meter. This greatly emphasized the resonance effects as might be expected. Under this circumstance it was found that small bits of dielectric introduced into the chamber altered markedly these otherwise sharp resonance effects. This immediately suggested methods for measuring the dielectric properties of materials at these extremely high frequencies.

If the material under investigation is a fluid it may be made to fill the entire chamber. In fact, the earliest experiments done on wave guides

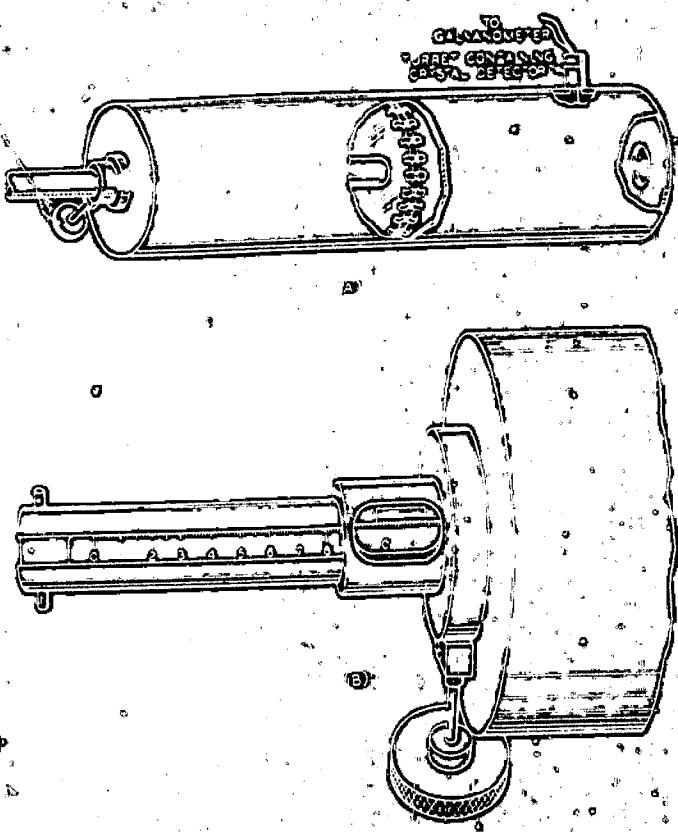


FIG. 5. Form of resonant cavity which may be used either as a wave meter or as means for investigating the properties of certain dielectrics.

were of this kind and used water as the dielectric.⁶ They were of such a character that both dielectric constant and absorption index of water could have been determined. It would appear that by this method absorption bands in gases such as the one for ammonia predicted by Dennison⁷ and discovered experimentally by Dr. Cleeton and Professor Williams⁸ could be located very accurately by such a scheme.

Indicators

It is often desirable to have available in the laboratory some kind of a wave indicator or probe such as shown in Fig. 6. It consists of a simple silicon detector in cartridge form, connected to a nearby microammeter. The former is mounted on a fiber 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 approximate orientation of the lines of electric force in the wave front as well as the general directive

pattern of the radiation. For the latter purpose it is desirable that the detector be as small as possible and that it not incorporate large amounts of absorbing dielectrics.

The characteristics of the silicon detector are, of course, well known. The one mounted in the resonant chambers shown in Figs. 4 and 5 has already been described.² 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.

Conclusion

The methods outlined above represent the first steps in a relatively new field of electrical measurements. Work is now in progress directed at measurements of electric intensity and power and accordingly of characteristic impedance and attenuation. The work already accomplished seems to point toward a simplification of measurements that according to the older methods

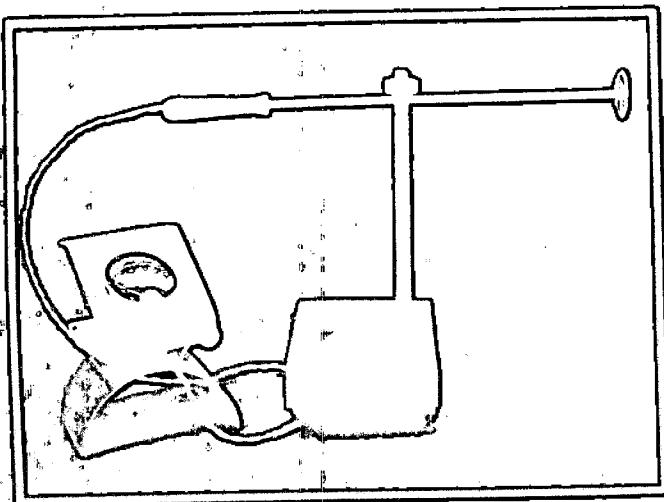


FIG. 6. Simple hand probe for investigating the presence of electric field in and around a wave guide oscillator.

were becoming increasingly more difficult as the frequency was raised.⁹ Fig. 7 shows various component parts of a laboratory set-up used for transmitting waves over a wave guide 380 meters in length.

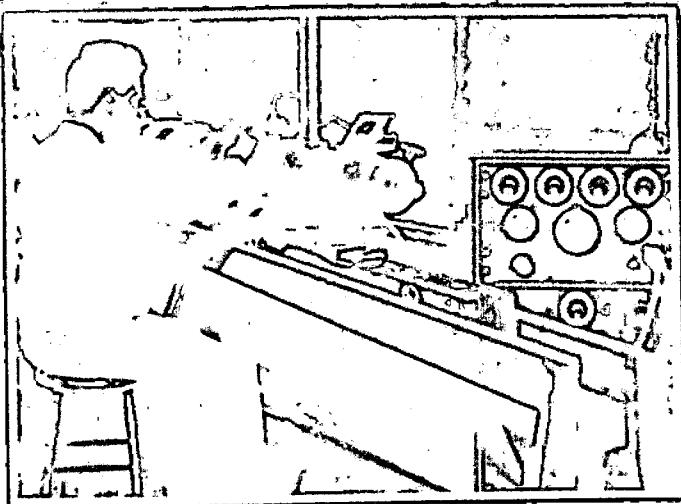


FIG. 7. Transmitting end of an experimental wave guide.

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1. The following papers dealing with this form of electrical transmission were presented at a joint meeting of the American Physical Society and the Institute of Radio Engineers in Washington, D. C., April, 1936.
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The relations between academic and industrial research in the physical sciences at the present time, the extent to which progress depends on team work, independent of whether the investigation is prosecuted within the university or within industry, the inspiration and assistance which academic and industrial research in these fields are continually bringing to one another, give fundamental research in the physical sciences special claims upon the support of industry, apart from the rapidity with which discoveries in this field are applied to industrial purposes.

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2. The possibility of transmitting electromagnetic waves through cylinders of dielectric and through hollow metal pipes was predicted mathematically by Lord Rayleigh in 1897. Subsequently Zahn (1916) and Schriever (1920) actually produced waves of this general type. The latter measured their velocity of propagation in cylinders of water.

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