Sept. 13, 1938. G. C. SOUTHWORTH 2,129,711

GUIDED TRANSMISSION OF ULTRA HIGH FREQUENCY WAVES

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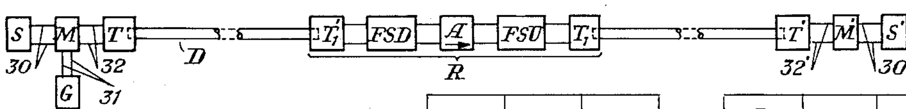


Fig. 1

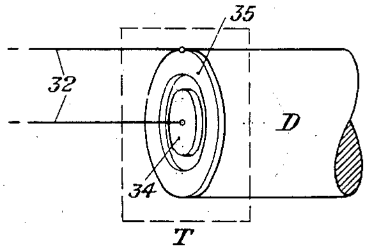


Fig. 2

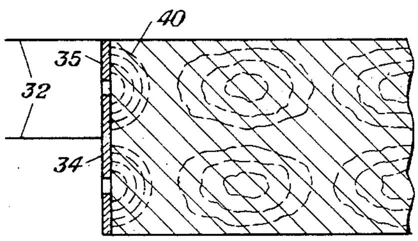


Fig. 3

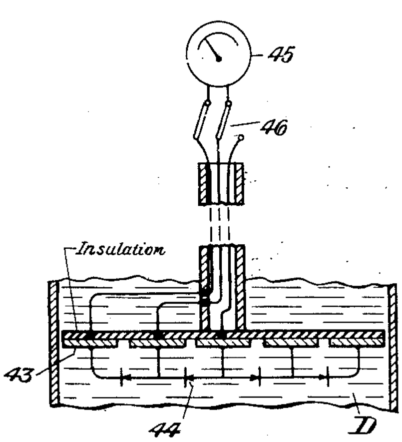


Fig. 10

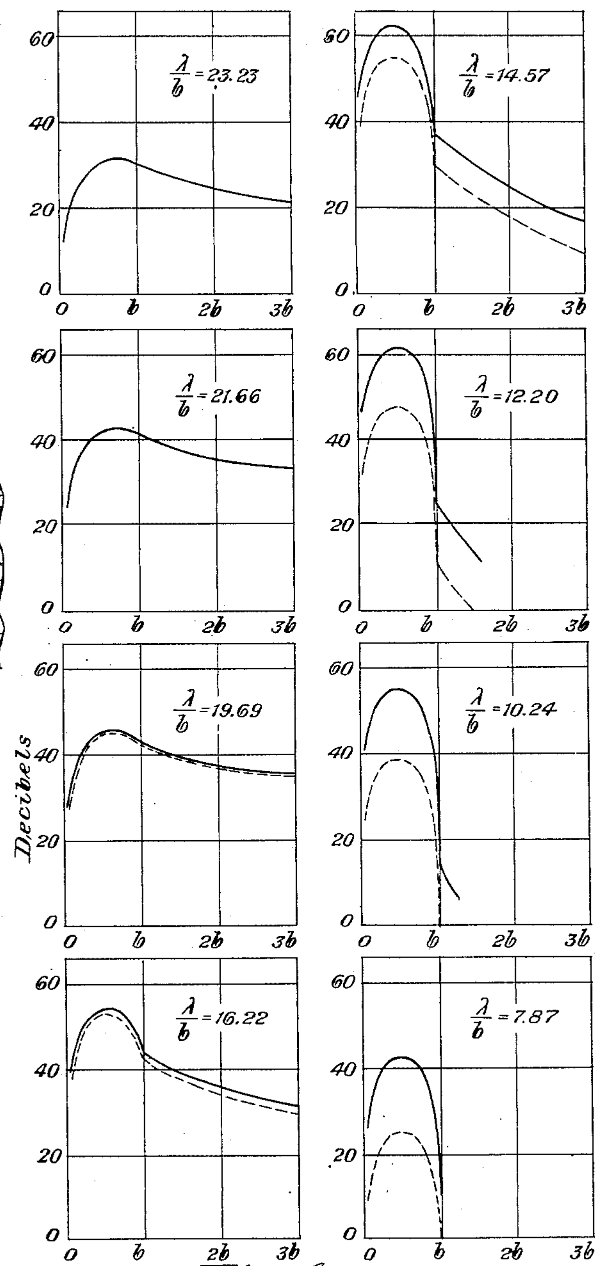


Fig. 4, $n = 9$

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GUIDED TRANSMISSION OF ULTRA HIGH FREQUENCY WAVES

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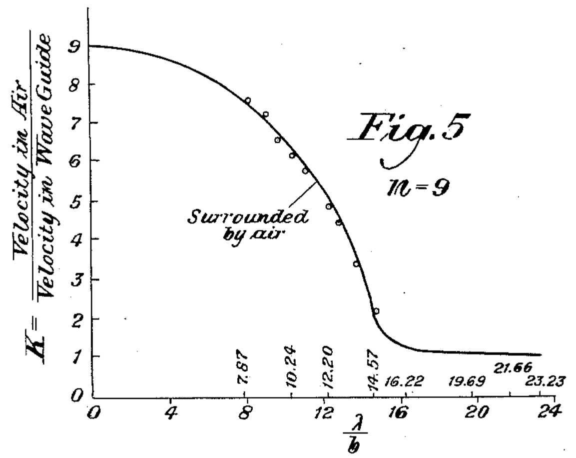


Fig. 5

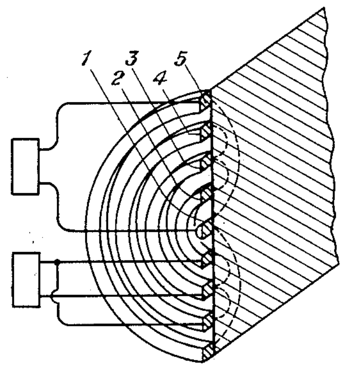


Fig. 7

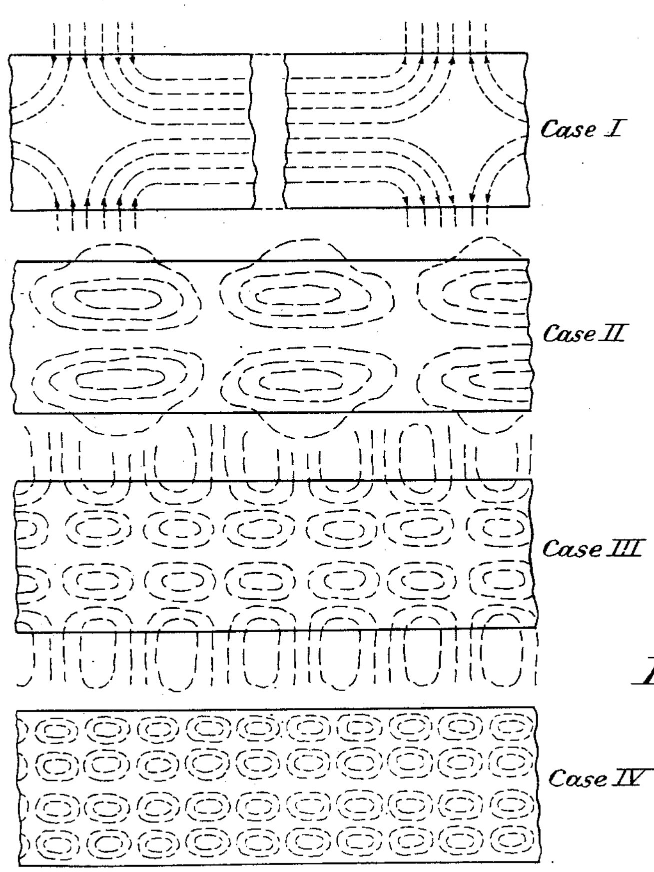


Fig. 6

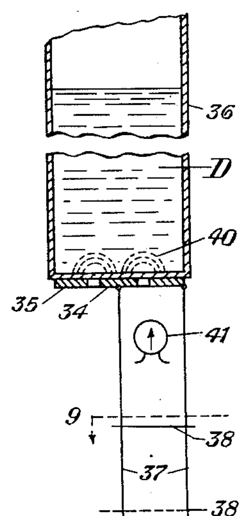


Fig. 8

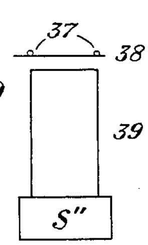


Fig. 9

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GUIDED TRANSMISSION OF ULTRA HIGH FREQUENCY WAVES

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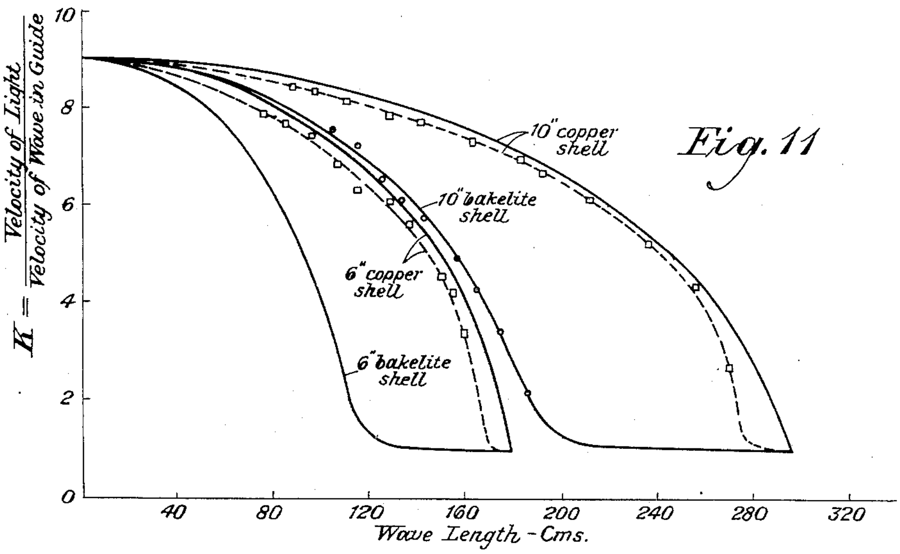


Fig. 11

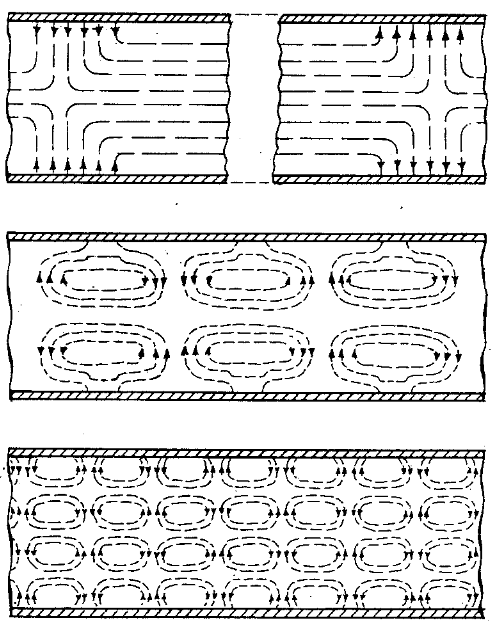


Fig. 12

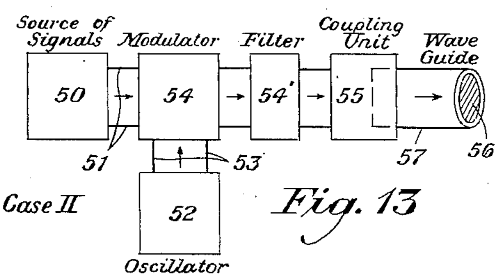


Fig. 13

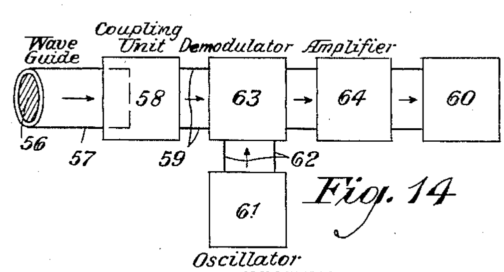


Fig. 14

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GUIDED TRANSMISSION OF ULTRA HIGH FREQUENCY WAVES

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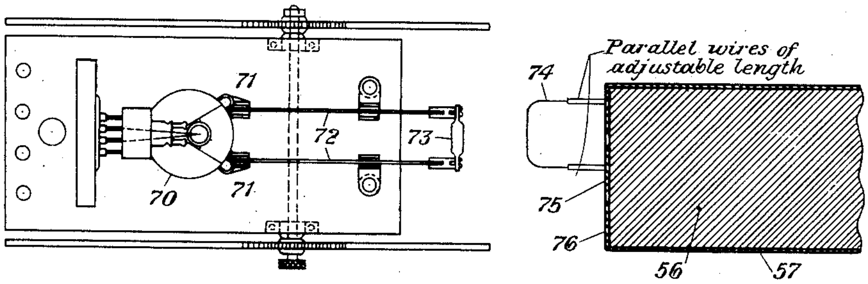


Fig. 15

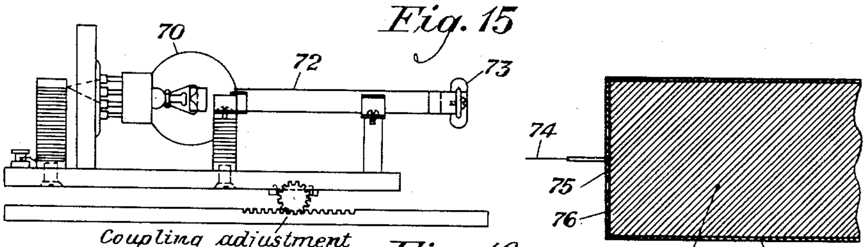


Fig. 16

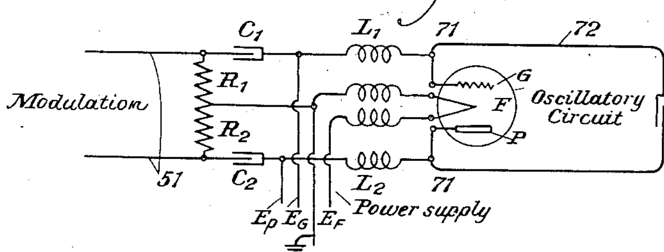


Fig. 17

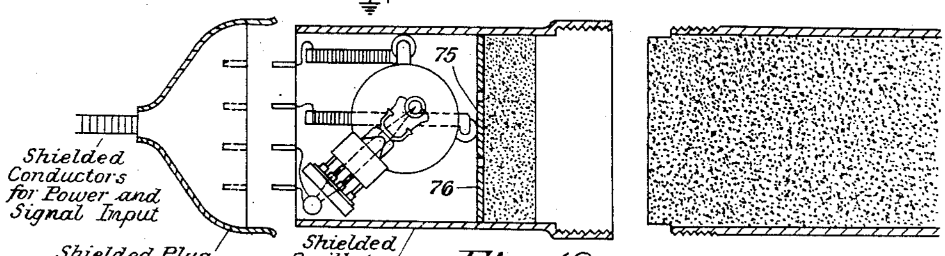


Fig. 18

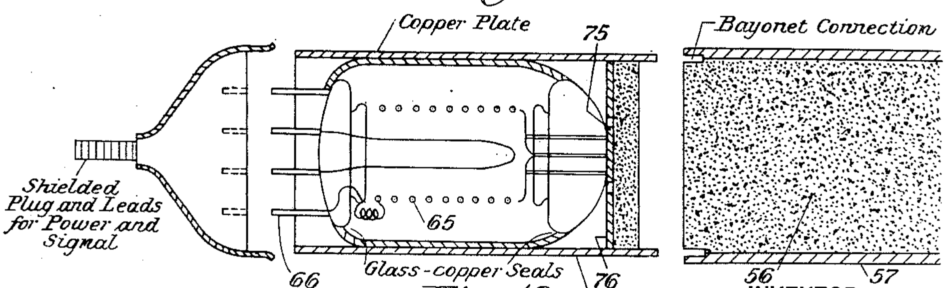


Fig. 19

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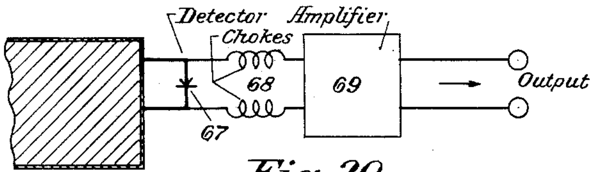


Fig. 20

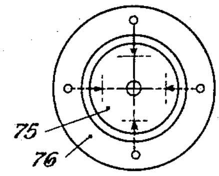


Fig. 21

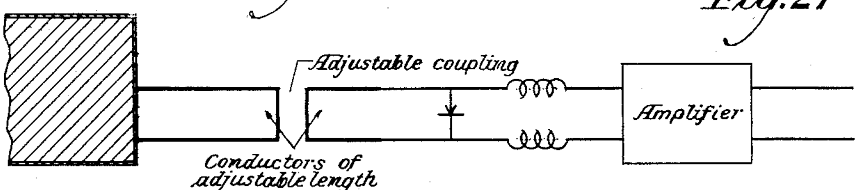


Fig. 22

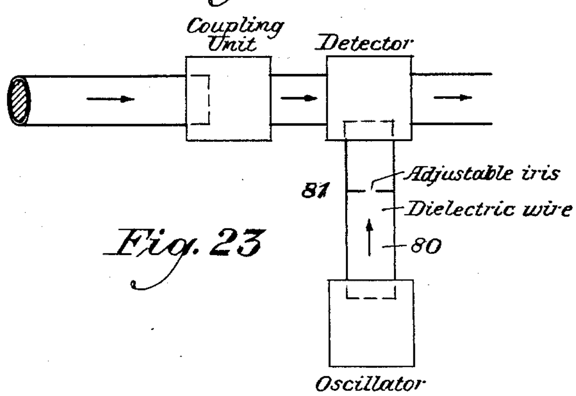


Fig. 23

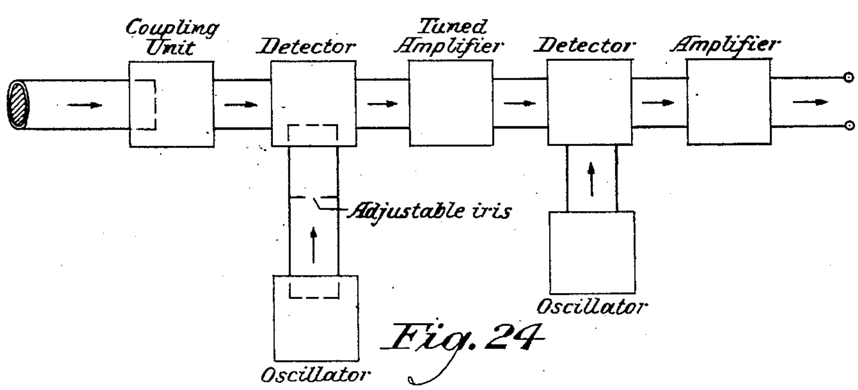


Fig. 24

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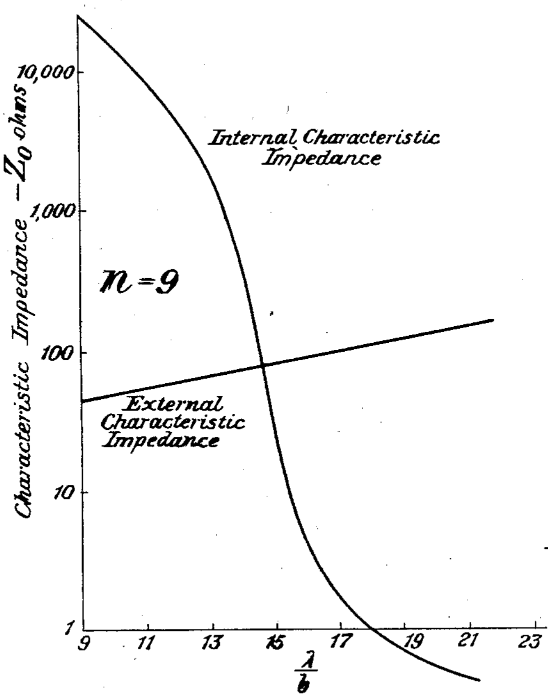


Fig. 25

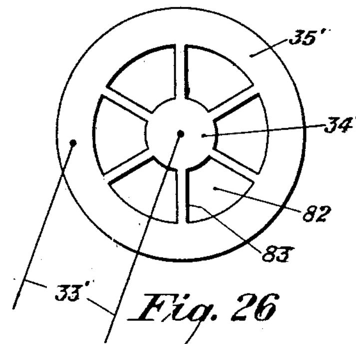


Fig. 26

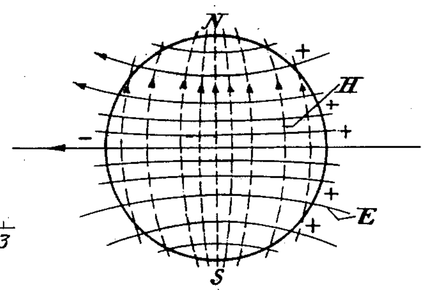


Fig. 27

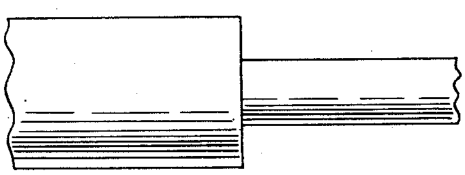

Fig. 29

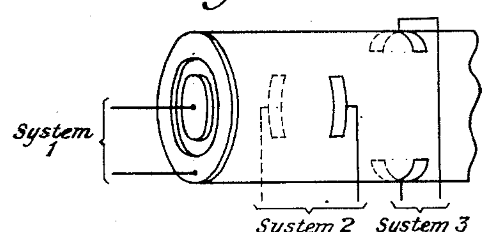


Fig. 28

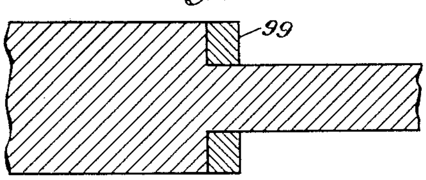


Fig. 29a

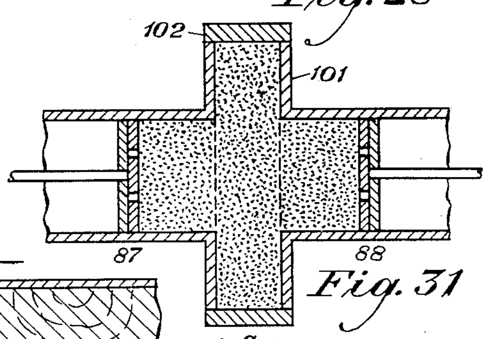


Fig. 31

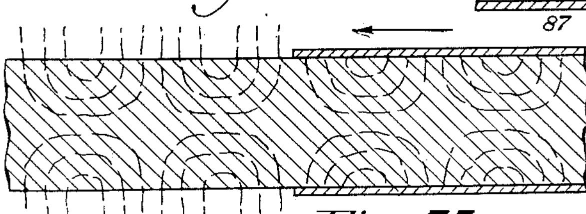

Fig. 35

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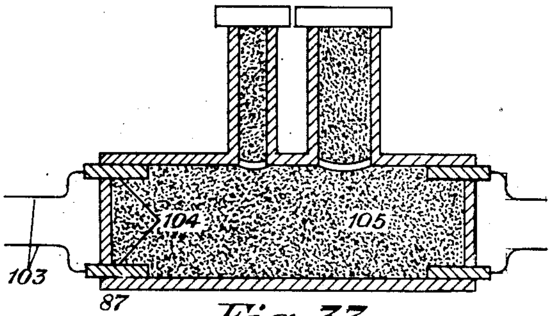


Fig. 33

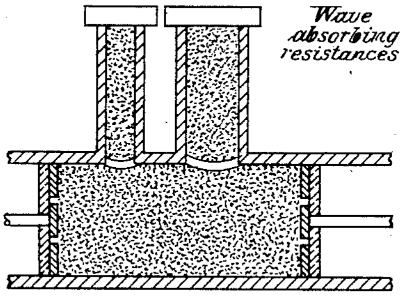


Fig. 32

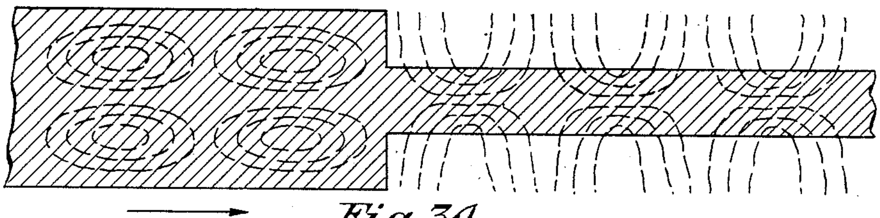

Fig. 34

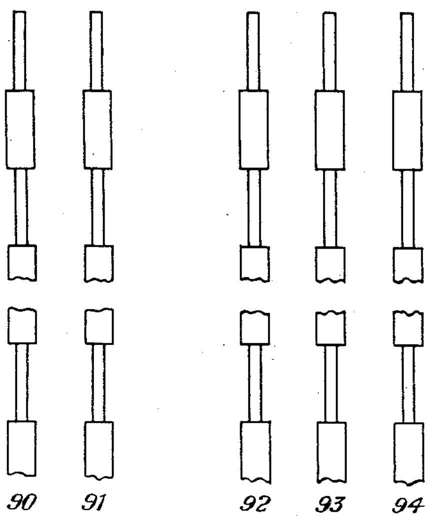


Fig. 36

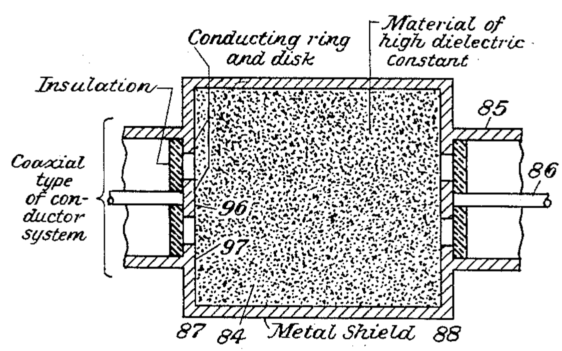


Fig. 30

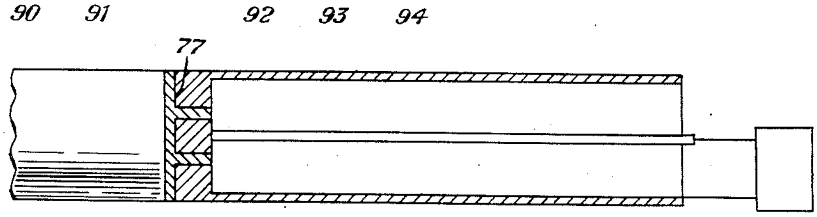


Fig. 37

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Patented Sept. 13, 1938

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# UNITED STATES PATENT OFFICE

2,129,711

## GUIDED TRANSMISSION OF ULTRA HIGH FREQUENCY WAVES

George Clark Southworth, Ridgewood, N. J., assignor to American Telephone and Telegraph Company, a corporation of New York

Application March 16, 1933, Serial No. 661,154

70 Claims. (Cl. 178—44)

An object of my invention is to provide a new and improved system for the transmission of electrical effects from one place to another place at a distance therefrom by means of electromagnetic waves associated with a dielectric guide extending between the two places. Another object of my invention is to provide for signaling along such a guide by means of such waves. Another object is to provide for the generation of high frequency electric conduction currents in a suitable medium and the application of their energy to generate corresponding "displacement" current waves for transmission along a guide of dielectric material. An object complementary to the foregoing is to provide for the translation of the energy of received displacement currents in a dielectric guide into conduction currents in associated receiving apparatus. Still another object is to provide suitable apparatus and a proper method so that electric waves may be transmitted along a dielectric guide without excessive dissipation of their energy in the guide or in the medium adjacent thereto. In some examples of my invention the guide employed may be partly dielectric and partly conductive.

All these objects and various other objects and advantages of my invention will become apparent on consideration of a limited number of examples of practice in accordance with the invention which I have chosen for presentation in this specification. It will be understood that the following disclosure relates principally to these particular examples of the practice of the invention and certain scientific principles involved in such practice, and that the scope of the invention will be indicated in the appended claims.

Referring to the drawings, Figure 1 is a simplified diagram of a system by which my invention may be practiced; Fig. 2 is a perspective diagram showing a coupling at one end of the dielectric guide that may be employed in practicing my invention; Fig. 3 is a corresponding sectional elevation; Fig. 4 is a set of curve diagrams giving electric and magnetic intensities for various frequencies in and about the dielectric guide; Fig. 5 is a curve diagram for wave slowness as a function of the wave length in relation to the radius of the dielectric guide; Fig. 6 is a set of diagrams showing wave shapes in an all-dielectric guide for different wave lengths; Fig. 7 is a perspective diagram showing apparatus for the generation of higher order waves of shorter wave length; Fig. 8 is a sectional diagram of apparatus for demonstrating the laws of guided dielectric waves by means of "standing waves"; Fig. 9 is a detail section on the line 9 of Fig. 8; Fig. 10 is a diagrammatic sectional view of certain testing apparatus for the standing waves in connection with Fig. 8; Fig. 11 is a curve diagram that extends the showing of Fig. 5 to different diameters of wave guides and to the case of composite wave guides each made up of a dielectric body surrounded by a metallic sheath; Fig. 12 is a set of diagrams for such a composite wave guide corresponding otherwise with Fig. 6; Fig. 13 is a diagram of sending end signaling apparatus for a dielectric guide; Fig. 14 is a corresponding diagram for the receiving end; Fig. 15 is a plan view of a generator and coupling for sending waves in a dielectric guide; Fig. 16 is a corresponding side elevation; Fig. 17 is a circuit diagram for the apparatus of Figs. 15 and 16; Fig. 18 is a section showing sending end apparatus alternative to that of Figs. 15 and 16; Fig. 19 shows still another alternative form of such apparatus; Fig. 20 is a diagram showing receiving end apparatus employing a detector; Fig. 21 is a diagrammatic end elevation showing how one or more detector units may be connected in the system of Fig. 20; Fig. 22 is a modification as compared with Fig. 20 and shows an adjustable inductive coupling; Fig. 23 shows receiving end apparatus with adjustable means for supplying the carrier current at the receiving end; Fig. 24 is a diagram illustrating the reception of signals in two successive stages; Fig. 25 is a curve diagram for characteristic impedance of an all-dielectric wave guide; Fig. 26 is a diagrammatic end elevation of a modified coupling electrode; Fig. 27 is a cross-section of the dielectric guide showing the lines of force for a certain case of polarization; Fig. 28 is a perspective diagram showing how multiplexing may be accomplished by the superposition of diametrically polarized waves; Fig. 29 is a diagram for one form of a high pass filter; Fig. 29*a* is a corresponding section, modified to comprise an absorbing member for unwanted energy; Fig. 30 is a diagrammatic view showing a high pass dielectric guide filter interposed in a concentric conductor system; Figs. 31 and 32 are diagrams for band pass filters; Fig. 33 is a diagram for a band pass filter for polarized waves; Fig. 34 is a diagram illustrating the phenomenon of radiation from a part of a dielectric guide having its diameter reduced for that purpose; Fig. 35 illustrates the same phenomenon attained by shielding the non-radiating part of the guide and leaving the radiating part unshielded; Fig. 36 is a diagrammatic broadside elevation of an antenna array based on the principle discussed in connection with Figs. 34 and 35; and Fig. 37 is a diagram of a device for modulating or detecting at the receiving end by means of a section of dielectric guide material having a non-linear characteristic.

As a result of theoretical studies and experiments I have determined that under certain conditions electric waves may be transmitted a considerable distance along a dielectric guide, and that such waves may be utilized for signaling along the guide. A system for signaling in this way is illustrated diagrammatically in Fig. 1. Various elements of apparatus are represented by "boxes," but certain of these may be broken apart into distinct elements or they may be consolidated with others as I shall show, for example, in Fig. 17, where the generator G and modulator M may be merged together in a unitary device. In Fig. 1 high frequency electric currents are generated in the generator G and passed along the conductor pair **31** to the modulator M. These currents from the generator G are of a single frequency, say 1750 megacycles per second. S is a source of electric currents of composite frequency, say ranging in cycles per second from 1,000,000 to 3,000,000. Thus, the currents from S comprise a "frequency band" having a band width of 2,000,000 cycles per second. If a greater width is needed it can readily be attained. These currents of from 1,000,000 to 3,000,000 cycles are signaling currents and by their wide band range they may carry a large amount of intelligence. For example, they may comprise a large number of voice telephone channels. It is known that a band width of about 3,000 cycles is sufficient for intelligible telephone transmission. With a guard band of 1,000 cycles at each end of the 3,000 cycle band, this means an appropriation of a 5,000 cycle band for each voice channel. Hence with the range of 2,000,000 cycles there may be 400 voice channels. That is, the system shown in Fig. 1 may represent a multiplex one-way transmission comprising 400 voice channels. Or, the symbol S may represent a source of a considerably greater number of telegraph channels. Or, it may represent both telephone and telegraph channels. Again, it may represent a band of currents obtained by means of a television sender. It is well known that for good television transmission a wide frequency band is necessary, and the range suggested by way of example for the source S in Fig. 1 would be suitable for good television transmission. Thus in general, the symbol S in Fig. 1 represents a source of currents extending over a wide frequency range and capable of carrying a large amount of intelligence expressed in signaling form.

The currents from the source S, ranging in frequency from 1,000,000 to 3,000,000 cycles, are applied through the conductors **30** to the modulator M to modulate the current of the frequency that I have assigned at 1,750 megacycles coming from the generator G. This frequency of 1,750 megacycles corresponds to a wave length in free space of about 17.1 cm. The output from the modulator M in the conductor pair **32** may comprise currents of the carrier frequency 1,750 megacycles and the upper and lower side bands, the upper side band ranging from 1,751 to 1,753 megacycles, and the lower side band ranging from 1,749 down to 1,747 megacycles. These high frequency currents going over the conductor pair **32** from the modulator M, will be delivered on the input side of the coupling device T. The structure and method of operation of this device T will be explained later in this specification. For the present it will suffice to state that it receives high frequency conduction currents on its input side through the conductors **32** and generates corresponding "displacement currents" in the proximate end of the dielectric guide D. Various specific designs that may be chosen for the guide D fall under two general classes that will be discussed later: (1) without associated metal elements; and (2) with such metal elements. For the present disclosure in connection with Fig. 1 it will be convenient to consider the guide D as of the first type. A guide of the second type will be considered in connection with Figs. 13 and 14.

As I have stated, the frequencies involved in the currents delivered over conductors **32** to the coupling device T lie in the range from 1,747 to 1,753 megacycles, which is a comparatively narrow frequency range, lying within about $^{17}/_{100}$ of 1 per cent above or below the carrier frequency. The wave length in free space being about 17.1 cm., the diameter of the dielectric guide D is of comparable magnitude, and it is assumed in this case to have a radius of 6.6 cm. These data and their relation and significance will be discussed more definitely farther along in this specification.

In Fig. 1 a repeater R is shown interposed between the sending end on the left and the receiving end on the right. If the attenuation from end to end is not too great, such a repeater will be unnecessary. According as the attenuation is greater, one repeater or more than one may be interposed at proper intervals.

Waves of displacement current will travel along the dielectric guide D from left to right, and will be received in the coupling device T′ whose function is the inverse of that of T. That is, at T′ the energy of the displacement current waves arriving in the dielectric guide D will be translated into conduction currents in the conductor pair **32′**. These conduction currents passing in the conductors **32′** will go to a detector M′, and its detected output current in the output conductor pair **30′** will comprise the various frequencies mentioned heretofore lying within the range from 1 to 3 megacycles. The conductors **30′** lead to a device S′ which comprises suitable means for performing the inverse function compared to S at the transmitting station. For example, if the intelligence transmitted should consist of a large number of telephone conversations on respective voice channels, the apparatus S′ will be employed for separating these various channels into respective conductor pairs at normal voice frequency. Or, the symbol S′ may represent apparatus for receiving television currents and translating them into the corresponding appropriate variations of luminosity to generate a moving picture at the receiving end corresponding to the changing scene at the transmitting end. If one or more repeaters R are employed, each may consist of a coupling device $T'_1$ like T′, a frequency-step-down unit FSD, an amplifier A, a frequency-step-up unit FSU, and a coupling device $T_1$ like T. If preferred, the step-up and step-down units may be omitted, and the amplifier may operate at high frequency.

For a discussion of the utilization of a wide frequency range for conveying a large amount of signaling intelligence, I make reference to the specification of the United States patent to Espenschied and Affel, No. 1,835,031, granted December 8, 1931.

Having indicated in connection with Fig. 1, in a general way, how a complete signal transmitting and receiving system may utilize a dielectric guide, I will now explain more in detail some principles involved in the generation and transmission of high frequency electromagnetic waves in a dielectric guide.

Referring to Fig. 2, this is a simplified diagrammatic representation of apparatus by means of which the theory of these waves may be explained in a particular case. D is a circular cylinder of dielectric material extending an indefinite distance to the right, and cut square across at the left. Its radius is $b$; this was taken at the value of 6.6 cm. in Fig. 1. Attached centrally on the circular end face of this cylinder D is a metal disc electrode **34**, and also attached concentrically around the edge of this circular end face is the annular plate electrode **35**. The two conductors **32** of Fig. 1 are connected respectively to these two electrodes **34** and **35**. Thus, in Fig. 2 the dotted line rectangle T corresponds to the box T in Fig. 1.

Assume that the current in the conductors **32** is of a single frequency varying harmonically, and that this frequency is within or about the frequency of the range suggested for the conductors **32** in Fig. 1. Then there will be "displacement currents" in the proximate end of the dielectric guide D corresponding to the conduction currents in the conductors **32**. Whereas Fig. 2 shows the end of the dielectric guide D in perspective, it has been redrawn in Fig. 3 to represent an axial or longitudinal section. The displacement currents in the dielectric guide D will extend along such paths as indicated by the dotted lines **40**. These lines may be looked upon not only as displacement current paths, but they are "lines of force" that wax and wane with the alternating electromotive force applied on the conductors **32**.

Under the circumstances assumed in connection with Figs. 2 and 3, we proceed to ascertain the nature of the displacement currents and the associated electric and magnetic forces in and about the dielectric guide D. If, at any point in or near this guide D, we represent the electric force as a vector by the letter E, and the magnetic force at that same point as a vector by the letter H, then, according to the laws of electromagnetism, we must have the following fundamental equations:

$$\nabla x H = \frac{1}{c}[K\dot{E} + 4\pi\sigma E] \qquad (1)$$

$$\nabla x E = \frac{1}{c}[-\mu\dot{H}] \qquad (2)$$

$$\nabla . H = 0 \qquad (3)$$

$$\nabla . E = 0 \qquad (4)$$

In these equations (1) to (4), $\nabla x$ is the differential operator sometimes called "curl," and $\nabla .$ is the differential operator sometimes represented by "div" for divergence; $c$ is the velocity of light in free space; and $\mu$, K and $\sigma$ are, respectively, the permeability, dielectric constant and specific conductivity of the medium under consideration. $\dot{E}$ and $\dot{H}$ represent respectively

$$\frac{\partial E}{\partial t} \text{ and } \frac{\partial H}{\partial t}$$

when $t$ is the independent variable time. From the symmetry of the figure (Fig. 3), it is obvious that the vector E lies in a plane containing the axis of the cylindrical guide D; in other words, this vector may be resolved into two components, one axial and the other radial, and it has no component perpendicular to these. Also, the vector H is tangential, that is, at any point it is perpendicular to the plane of the corresponding radial and axial components of E.

By suitable steps, solutions may be deduced from the foregoing Equations (1) to (4) that are physically appropriate to the conditions of the present problem. These solutions, put in convenient form for our purpose, are as follows:

For the region outside of the dielectric guide D:

$$E_r = i\beta y J_0(y) H_0'\left(\frac{r}{b}x\right) e^{i(\beta z - \alpha c t)/b} \qquad (5)$$

$$E_z = xy J_0(y) H_0\left(\frac{r}{b}x\right) e^{i(\beta z - \alpha c t)/b} \qquad (6)$$

$$H_\phi = i\alpha y J_0(y) H_0'\left(\frac{r}{b}x\right) e^{i(\beta z - \alpha c t)/b} \qquad (7)$$

For the region inside the dielectric guide D:

$$E_r = i\beta x H_0(x) J_0'\left(\frac{r}{b}y\right) e^{i(\beta z - \alpha c t)/b} \qquad (8)$$

$$E_z = yx H_0(x) J_0\left(\frac{r}{b}y\right) e^{i(\beta z - \alpha c t)/b} \qquad (9)$$

$$H_\phi = i n^2 \alpha x H_0(x) J_0'\left(\frac{r}{b}y\right) e^{i(\beta z - \alpha c t)/b} \qquad (10)$$

These Equations (5) to (10) are expressed in cylindrical coordinates, the coordinate $z$ being measured along the axis of the cylindrical guide and the coordinate $r$ being measured radially. $E_z$ and $E_r$ are the corresponding components of the electric force E at the point whose coordinates are $z$, $r$, and at the time $t$. $H\phi$ is the magnetic force at the same point and same time. For any given value of these coordinates $z$ and $r$, each of $E_r$, $E_z$ and $H\phi$ is a single valued function of time $t$.

Each of the Equations (5) to (10) has the common factor $e^{i(bz-\alpha ct)/\beta}$, and it will be recognized at once that in the exponent of $e$, the term $-i\alpha ct/b$ represents the variation with time, and the term $i\beta z/b$ represents the propagation along the wire, involving the attenuation, whatever that may be. That is, $\beta$ is in general a complex number and its imaginary component represents attenuation. The absolute value of this imaginary component of $\beta$ will be relatively small, and for our present purpose it will not be advantageous to consider it further, and we shall assume that $\beta$ is a real number. This simply means that we are ignoring attenuation along the line but we are getting the relative wave forms with substantial accuracy, and when we interpret our equations as in Fig. 4, which will be discussed presently, it will be seen that we deal with relative intensities and our conclusions are equally applicable no matter what the attenuation.

Therefore, for the present purpose, we define $\alpha$ and $\beta$ as follows:

$$\alpha = 2\pi b/\lambda \text{ and } \beta = 2\pi b/L \qquad (11)$$

where $\lambda$ is the wave length as it would be in free space at the given frequency of the electromotive force that is applied across the electrodes **34** and **35** in Figs. 2 and 3, and L is the wave length as it is for propagation at that frequency along the guide D. For some purposes it is convenient to notice, as may be seen from Equation (11), that $\alpha$ or $\beta$ is the circumference of the guide D measured in wave lengths $\lambda$ or L respectively.

Other constants and dependent variables of the foregoing Equations (5) to (10) are defined as follows:

$$x=\sqrt{S_1^2\alpha^2-\beta^2} \text{ and } y=\sqrt{S_2^2\alpha^2-\beta^2} \quad (12)$$

where $S_1$ is the wave slowness (reciprocally proportional to velocity) for a medium such as exists outside and around the guide D, and $S_2$ is the wave slowness for a medium such as within said guide. More specifically, in the present case, $S_1=1$ and $S_2=n$, where $n$ is the so-called index of refraction of the material of the guide D; $n^2$ is equal approximately to the dielectric constant. This index of refraction $n$ is to be taken at its value for the range of frequencies involved.

$J_0(y)$ is the Bessel function of $y$ of zero order, and $J_0'(y)$ is its first derivative with respect to $y$.

$H_0(x)$ is the Hankel function of $x$ of zero order, and $H_0'(x)$ is its first derivative with respect to $x$.

(These functions $J_0$, $J_0'$, $H_0$ and $H_0'$ for the particular values of the respective arguments involved may be ascertained from suitable tables as, for example, Jahnke and Emde's Funktionentafeln, published in 1909 by B. G. Teubner in Berlin.)

Incidentally, it may be noticed that the coordinates $z$ and $t$ enter Equations (5) to (10) only in the factor $e^{i(\beta z-\alpha ct)/b}$, which is common to all these equations and from which it is apparent that the electrical and magnetic effects in and about the guide D constitute a wave transmission.

From Equations (5) to (10) and having reference to the data on which they are based, information may be deduced to enable us to plot the lines of electric force in and near the guide D. To get this information involves somewhat tedious computations which may be facilitated somewhat by the employment of graphical methods. The value of H must approach one and the same limiting value as $r$ approaches $b$, whether this approach is from within or without the guide D, that is, whether $r$ approaches $b$ with increasing or decreasing values; this consideration yields the equation:

$$\frac{1}{n^2}\frac{H_0'(x)}{xH_0(x)}=\frac{J_0'(y)}{yJ_0(y)} \quad (13)$$

where $y$ is real and $x$ is imaginary. For any particular value of $n$, we may make a graph of this Equation (13) and from it we may read off corresponding values of $x/i$ and $y$. We assume representative values of the frequency (expressed in the wave length $\lambda$, on which $x$ and $y$ are dependent) and from these and from our graph we get the corresponding values of $x/i$ and $y$. From these values, $\beta$ may be calculated by use of Equation (12) above.

Further employing these values in Equations (5) to (10) we get the corresponding values for the components of E and for H. Having the components of E, we may combine them to get the magnitude of E. For a concrete example, assume the value of the index of refraction $n$ to be taken as 9 (this is the approximate value for pure water), and assume various representative frequencies expressed in the ratio $\lambda/b$; thus the curves of Fig. 4 are obtained. In these curves the intensities of the radial electric force E (continuous lines) and magnetic force H (dotted lines) are plotted as ordinates against radial distances $r$ (in terms of radius $b$ as unit) as abscissas. These intensity ordinates are purely relative (in decibels above an arbitrary level); hence they serve for any point along the length of the guide D, that is, for any value of $z$, no matter what the attenuation may be from the origin to that point. It will be understood that at any given point whose coordinates are $z$ and $r$, the actual intensities vary sinusoidally at a frequency corresponding to the wave length $\lambda$. In each of the Equations (5) to (10) this variation is expressed in the common factor $e^{i(\beta z-\alpha ct)/b}$, as has been stated heretofore. The ordinates in the diagrams of Fig. 4 may be regarded as expressing the relative "effective" or "root-mean-square" values.

According to Fig. 4, it will be seen that at the comparatively low frequency for which $\lambda=23.23b$, the forces are not much less outside the guide D than within it, and are of considerable magnitude at points as far distant from the axis of the guide as three times its radius. This state of affairs may be expressed by saying that the energy of the waves resides largely in the space outside the guide D. With increasing frequency (that is, with decreasing values of $\lambda/b$), we pass along the series of diagrams of Fig. 4 and find the forces are relatively less and less intense without the guide until at the comparatively high frequencies corresponding to $\lambda=10.24b$ and $\lambda=7.87b$, the energy of the waves resides almost wholly within the guide D.

Utilizing such graphs of $x/i$ against $y$ as mentioned heretofore, we may obtain values of the ratio $\beta/\alpha$, which I call the "slowness factor" and designate by K. This quantity corresponds to the velocity of propagation of the actual waves as they exist, having their energy partly within and partly without the guide D. Fig. 5 gives values of K as ordinates for various frequencies expressed in terms of $\lambda$, the wave lengths as they would be in free space, as abscissas; a reason for introducing this Fig. 5 is that its immediate data are susceptible of experimental verification, as will be pointed out presently. It will be noticed that the parameters that distinguish the various diagrams of Fig. 4 are particular values along the scale of abscissas of Fig. 5. The frequencies increase as we go along the scale of abscissas from right to left in Fig. 5. At the lower frequencies on the extreme right the velocity is the same as in free space, and indeed we have seen that at these frequencies there is no substantial wave propagation within the guide. But at a critical frequency value corresponding to Equation (16) to be considered presently, we begin to have waves in the guide and these are propagated at velocities less than in free space, as indicated by the upward bend of the curve of Fig. 5. Then at yet higher frequencies the velocity of propagation in the guide approaches as a limit the value which it would have in an unbounded medium of the same material as the guide, this value corresponding to the index of refraction $n$, which we have given the particular value 9 in the present instance.

The diagrams of Fig. 6 are compiled from data that have been explained heretofore, including Fig. 4 on which especially Case II of Fig. 6 is based. These diagrams are not rigorously exact; they are intended to show the main trends of the lines of force at different wave lengths. A few points of these lines of force have been computed, but to a considerable extent they have been completed by interpolation and extrapolation. We assume a fixed instant of time $t$, and the same value of $n$ as before, namely $n=9$. Having ascertained the values of E for Fig. 4 by combining the component values, we have those components already available, and from them we get the slope of E at each of various points corresponding to various coordinate pairs $z$ and $r$. Waves of different length may be superposed in the dielectric guide D, but for clearness as well as for other reasons I show the different wave lengths in different parts of Fig. 6, which I distinguish as Cases I, II, III and IV. A three-dimensional picture of the fields depicted in Fig. 6 may be obtained by imagining the figures illustrating each of the four cases to be rotated about the axis of the guide so that the electric lines describe surfaces of revolution.

*Case I.*—Here we assume the frequency at such a low value, that is, the wave length is so great, that propagation first becomes possible. This being a critical or limiting condition of affairs, special mathematical procedure is necessary which it will not be necessary here to set forth, except very briefly as follows: In connection with the derivation of Equations (5) to (10) from Equations (1) to (4), it may readily be shown that $\beta$ may take any value between the limits given by

$$n^2\alpha^2 \geqq \beta^2 \geqq \alpha^2 \qquad (14)$$

and that no wave power will be propagated through the guide D until the frequency is sufficiently high to satisfy the relation

$$y = 2.40 = \sqrt{n^2\alpha^2 - \beta^2} \qquad (15)$$

This relation obtains when $J(y)=0$, of which last mentioned equation, $y=2.40$ is a root. Subject to the condition expressed in Equation (15), $x=0$ and $\alpha=\beta$ and therefore $\lambda=L$, which means that the effect in and about the guide D is propagated with the velocity of light in free space. We ascertain that outside the guide the lines of electric force are everywhere radial, inside and near the axis they are parallel with the axis, and inside and near the boundary they are radial. These general characteristics of the field are depicted in the diagram of Fig. 6 labeled "Case I". The longitudinal electric intensity in both "Case I" and "Case II" is maximum at the axis of the guide and it varies with respect to time and also with respect to distance along the guide in the same manner as the applied electromotive force, sinusoidally, therefore, in the case of a sine wave source. Accordingly, there is a longitudinal flow of displacement current through the dielectric medium. The accompanying magnetic field may be represented by closed loops concentric with the guide and disposed in planes transverse to the axis.

*Case II.*—Here we assume the frequency at such a value that $\lambda/b=13.5$. This determines $\alpha$, $\beta$, $x$ and $y$, and accordingly we get the values of E as a function of $z$ and $r$; the corresponding lines of force are plotted in the part of Fig. 6 designated "Case II". It should be noticed that the value of $\lambda/b=13.5$ which was chosen for this case, lies between the values for the fifth and sixth diagrams of Fig. 4.

*Cases III and IV.*—With increasing frequencies, waves of higher order appear as may be deduced by proceeding further in consideration of the same data that were relied on for Cases I and II. Thus, $y=2.40$ is not the only root of the equation $J(y)=0$; there are other roots, $y=5.52$, $y=8.65$, etc. It is in connection with such higher values for $y$ that we learn of the possible existence of these higher orders of waves, but for the purpose of this specification it will not be necessary to do more than illustrate them qualitatively, as has been done in the parts of Fig. 6 labeled "Case III" and "Case IV." In these two cases the longitudinal electric intensity and displacement current flow are maximum at the axis of the guide and also at a cylindrical surface lying between the axis and the periphery. The accompanying magnetic field may be represented by closed loops concentric with the guide; and with respect to the radial direction it varies in accordance with a Bessel's function from a zero value at the axis.

When desirable to transmit over a dielectric guide by means of higher order waves such as illustrated in Cases III and IV of Fig. 6, their generation may be facilitated by employing concentric annular electrodes at the sending end, as illustrated by way of example in Fig. 7. In this case five such electrodes are shown, numbered consecutively from the center. Those numbered **2** and **4** are conductively connected and energized in opposite phase with the intermediate electrode **3**, so that there will be two sets of lines of force **2—3** and **3—4**, as shown in Fig. 7, and these will be snapped off and propagated along the dielectric guide D in closed loops constituting electric displacement current waves, as shown in Case III of Fig. 6.

These higher order waves may be utilized for multiplexing. Thus, in Fig. 7 lines of force are also shown extending between the central electrode **1** and the outer electrode **5**. These lines of force are due to superposed electromotive forces of appropriate lower frequency generated in the circuit associated with these electrodes. In this way we may have superposed in one and the same dielectric guide D a system of waves corresponding to Case II of Fig. 6 and a system of waves corresponding to Case III of the same figure. Similarly, higher orders of waves may be generated and transmitted, as in Case IV of Fig. 6, and various superpositions of waves of lower order may be practiced in that connection.

We have already seen that at the critical value of $y=2.40$, $\alpha=\beta$, and from equations (11) it is further apparent that $\alpha=\beta=2\pi b/\lambda$. Substituting these values in the second of equations (12) we get the result that

$$\lambda_c = 2.61 b\sqrt{n^2-1} \qquad (16)$$

where $\lambda_c$ is the critical wave length below which propagation is not possible and above which it becomes possible. The beginning of this possibility is shown in Case I of Fig. 6. For illustrative purposes we have assumed that $n=9$, and introducing this value in Equation (16) we get $\lambda_c=23.33b$. It will be seen that the first diagram of Fig. 4 has a value for $\lambda$ only slightly less than this critical value $\lambda_c$, and it is this value which is employed in Case I of Fig. 6.

From Fig. 4 we see that in the case of wave lengths not much less than $\lambda_c$, the wave power resides partly in the guide but to a great extent in the surrounding space, and from Fig. 5 we see that in this case propagation is at velocities little less than of light in free space. As the frequency is increased, more and more of the power comes to reside in the guide as illustrated in Case II of Fig. 6, and turning to Fig. 5, the velocity of propagation decreases toward a limiting value which is the characteristic velocity in an unbounded medium of the same material as the guide. With increasing frequencies, higher order waves may appear at certain shorter critical wave lengths, as indicated in Cases III and IV of Fig. 6.

In connection with Fig. 1, the wave frequency was suggested to be taken at 1,750 megacycles, and an alternating electromotive force of this frequency was generated and applied at the sending end of the system of Fig. 1. This frequency gave us a wave length in free space of 17.1 cm. Substituting this value of $\lambda$ in Equation (16) and solving for $b$, we get

$$b_c = 6.54/\sqrt{n^2-1} \qquad (17)$$

where $b_c$ is the critical radius which is at the least value possible for propagation corresponding to Case I of Fig. 6.

In connection with Fig. 1 it was suggested that the radius of the guide D might properly have a value of 6.6 cm. The basis of this assignment was as follows. In Equation (16) for the critical wave length at which propagation is impossible on one side and possible on the other side, we have the constant factor 2.61. This corresponds closely with the first of the diagrams of Fig. 4. Guided by the sequence of these diagrams and other considerations, we arbitrarily alter this constant to a value about 40 per cent less, that is, we make it 1.5, and thereby we get the equation for a practical wave length,

$$\lambda_p = 1.5b\sqrt{n^2-1} \qquad (18)$$

This we regard as a practical relation for the propagation of waves with substantial effect along the dielectric guide. It should not be inferred that the wave length could not be shorter or even longer.

In connection with the theoretical study that began herein with Equations (1) to (4), we have assumed a value, $n=9$, for illustrative purposes and also because it enters largely into experimental verification of this theoretical work, as will be described presently. For variety of illustration, we assume the alternative value, $n=2$, for the guide D of Fig. 1. Already, in connection with Fig. 1, we have assigned 1,750 megacycles as a practicable frequency and have noticed that this corresponds to a wave length $\lambda$ of 17.1 cm. in free space. Substituting these values of $n$ and $\lambda$ in Equation (18) and solving for $b$, we get $b=6.6$ cm., which is the radius given heretofore for the guide D in Fig. 1.

In addition to a mathematical study like the foregoing, I have made experimental studies of these displacement currents in the dielectric. Of course, the vectors represented by E and H in connection with Figs. 2 and 3, are elusive for experimental study, traveling as they do with velocities comparable with the velocity of light, or varying at any one place with frequencies of the order of a thousand million per second. But, it is a well known device in the study of wave transmission, to set up "standing waves," and I will indicate how this can be done for these guided dielectric waves. Referring to Figs. 8 and 9, the tall vessel **36** of circular crosssection has a wall of suitable dielectric material such as bakelite. The diameter is made large enough so that the interior is conveniently accessible. This vessel **36** may be filled with water D, or other suitable liquid dielectric, to any desired height. The column of water within the vessel **36** is the dielectric corresponding to the guide D in Figs. 2 and 3. It is made tall enough so that it can have a system of stationary electric waves set up therein, but there is no need to make it taller than necessary for this purpose. The bakelite wall is thin so that its presence can be neglected in respect to the electric wave effects.

The bottom wall of the vessel **36** is a thin horizontal plate of dielectric material, and attached to the bottom wall and coaxially arranged with the cylindrical vessel **36** are the central disc electrode **34** and the surrounding annular electrode **35**. A pair of Lecher wires **37** hang vertically with their upper ends conductively connected respectively to the electrodes **34** and **35**. At **38** is an adjustable conductive bridge that may be clamped at any desired height. A source of high frequency oscillatory currents is represented at S'' in Fig. 9 and these currents flow in a circuit comprising the conductor **39** bent around three sides of a rectangle. This source S'' is positioned (see Fig. 9) to bring the intermediate side of the rectangular frame **39** close to and parallel with the bridge **38**. Thus, the oscillatory currents in the circuit **39** induce electromotive forces of the same frequency in the bridge **38**, and the corresponding induced currents flow in the portion of the Lecher wire conductors **37** between the bridge **38** and the electrodes **34** and **35**. The complete circuit of these induced currents comprises the path of the displacement currents in the dielectric material D within the vessel **36**, this path being represented by the dotted lines of force **40** in Fig. 8.

A reason for interposing the Lecher wire system between the source S'' and the dielectric guide D in Fig. 8 is that it serves as a convenient intermediate coupling that is capable of a wide range of adjustment, and it permits of impressing on the dielectric a definite and measurable electric force. By adjustment of the bridge **38** one may ascertain the wave length and corresponding frequency of the source S''. A microammeter **41** to which is connected a small rectifier is held with its terminals near the two Lecher wire conductors **37** so as to pick up a small portion of the wave power in this circuit. Starting with the bridge **38** close to the electrodes **34** and **35**, it is then adjusted away therefrom till the microammeter reading is a maximum. Then we know that the distance from the bridge **38** to the electrodes **34** and **35** is a fraction of a wave length, just how much depending on the configuration and properties of the associated elements at the upper ends of the Lecher wires **37**.

By adjusting the bridge **38** further downward, the intensity reading on the meter **41** diminishes to a certain value and then increases to another maximum as with the bridge at **38'**. Then we know that the distance between the two positions of the bridge, that is, the distance from **38** to **38'**, is a half-wave length. Knowing that the waves associated with the Lecher wires travel with the velocity of light in space, the frequency can easily be computed from the wave length.

The standing waves in the water column of Fig. 8 were demonstrated in three ways. The first of these will now be described. Varying the height of the water column within the vessel **36**, and relying on the meter **41** as shown in Fig. 8, we find that at certain water levels the intensity indicated in the meter is a maximum and at others a minimum. If we vary the height of the water column from one maximum to the next maximum, we know that we have increased its height one-half wave length. Thus we can demonstrate the presence in the dielectric guide D of the electric waves corresponding to those discovered by a theoretical study such as was presented above in connection with Figs. 2 and 3 and Equations (1) to (4).

According to a second procedure for demonstrating standing waves in the water column D, the container was nearly filled with water and the Lecher wires were adjusted for resonance. A horizontal circular disk of sheet copper which contacted the walls of the column D was then lowered into the water. Its effect at various heights in limiting the top of the wave range was the same as changing the water level. Here the meter **41** is used in the same way as in the first method. Inasmuch as the energy of the waves under some conditions lies partly outside but adjacent to the dielectric guide, I provided an adjustable annular plate around the container for the water column D, and adjusted it to lie in registry in the same horizontal plane with the copper disk just mentioned.

In a third method of demonstrating the standing waves, a composite disk plunger was employed in somewhat the same way as the simple disk in the second method, but in this case the disk was made up of annular copper electrodes **43** with "water-proofed" crystal detectors **44** connected between consecutive electrodes. This is shown in Fig. 10. Connecting wires were brought out to an external microammeter **45** which indicated the maximum effects, and these could be readily correlated with the vertical adjustments of the disk. By means of the switches **46** the electric forces could be tested at various distances from the axis of the guide D.

Of these three methods the second was found to be most practicable, and was most generally used.

By adjusting the frequency of the source S'' of Fig. 9 to various values, we can get experimental results corresponding to the results that were deduced by mathematical reasoning in connection with Figs. 2 and 3. For example, at low frequencies, that is, below the critical frequency given by Equation (16), the presence of waves in the dielectric D cannot be discovered, but at frequencies only a little higher, the presence of electric force becomes measurably apparent, both within the vessel **36** and around it, showing that the lines of force within the dielectric D extend out into the adjacent space. Exploring for longitudinally directed forces outside the vessel **36** but adjacent thereto, we find that these forces wax and wane as we go along the length of the vessel. Also at any location in this region, if the direction of test for the exploring meter is turned from a longitudinal direction to tangential, a difference of effect is generally apparent, and this is different at different places. By such exploratory tests we are able to make substantial checks on the theory that has been developed in connection with Equations (5) to (10).

By tests at adjustments for various wave lengths the data were observed that have been plotted as points near the curve of Fig. 5. Their proximate agreement with the theoretical curve of that figure confirms it and the associated theory as truly representing the actual phenomena in a dielectric guide.

It will be understood that the apparatus shown in Figs. 8 and 9 is presented for the purpose of illustrating some theories that are involved in or linked with the invention. This is accomplished by an experimental study of conditions and processes in a dielectric guide, such as can be made by means of standing waves.

The dielectric guide of my invention may comprise parts of different properties, as for example, it may consist of a core and one or more concentric cylindrical shells of different dielectric constants. Again it may consist of a dielectric member associated with a conductive member or members, extending longitudinally therewith. Examples that are amenable to theoretical and experimental study are:

1. To surround the cylindrical dielectric guide with a conductive cylindrical shell.

2. To provide a conductive axial core along the cylindrical dielectric guide, and

3. To provide both such shell and core.

On the theoretical side, a study may be made of each of these cases similar to the study that was made for Fig. 2, starting with the same general Equations (1), (2), (3) and (4) from which the start was made for the dielectric guide without any associated conductive member. The first of the foregoing three cases may be treated the same as the case of the all-dielectric guide to the point where the boundary conditions are set up. In such case of a composite guide we have in place of Equation (13), the condition that $E_z=0$ when $r=b$. This yields equations similar to (8), (9) and (10) for the region inside the guide. It is obvious that there will be no appreciable field outside the guide. It will not be necessary to write out these equations as the principles involved have been illustrated for the earlier case.

The case of a dielectric guide surrounded by a conducting sheath differs from that of an all-dielectric guide in that waves are possible when the dielectric has any index of refraction whereas in the case of the all-dielectric guide the index of refraction must in general be greater than unity. A special case of this guide having the more general range of index will therefore be that of a hollow conductor either evacuated or filled with air or other gas.

It may be established that for a guide of dielectric material within a metallic cylindrical shield

$$K=n\sqrt{1-\lambda/\lambda_c} \text{ (approximately)} \qquad (19)$$

where K is the slowness factor as defined in connection with Fig. 5; $n$ is the index of refraction of the dielectric material of the guide; $\lambda$ is the wave length in free space corresponding to an assigned frequency; and $\lambda_c$ is the critical wave length in free space such that at frequencies for which $\lambda<\lambda_c$ there is propagation, but at frequencies for which $\lambda>\lambda_c$ there is none. Fig. 11 should be compared with Fig. 5. In Fig. 5 the abscissas are in terms of the radius of the guide, whatever that may be. In Fig. 11 the abscissas are in centimeters, and four different guides have been represented, corresponding to Fig. 8. Two of these are all-dielectric, respectively 10 and 6 inches in diameter. Points were ascertained experimentally and plotted as shown for the 10-inch all-dielectric guide. Also, by means of the foregoing Equation (19) the theoretical continuous line curves were plotted in Fig. 11 for composite guides, respectively 10 and 6 inches in diameter. In all these guides the dielectric was water. In the all-dielectric guides the water was within thin cylindrical bakelite shells and in the composite guides the water was within cylindrical copper shells. Points were ascertained experimentally for both composite guides and these have been plotted in Fig. 11 and the dotted line curves sketched to correspond therewith.

The optimum diameter of a shielded dielectric guide may be regarded as depending on the relative dissipation losses suffered respectively in the dielectric core and the metallic shield. At the lowest frequencies at which dielectric waves are possible in such a guide, the wave power may be supposed to reside near the exterior, so that the shield may be expected to contribute considerable loss. At extremely high frequencies the field resides nearer to the axis of the core, and the shield may play a relatively unimportant part and the dielectric losses may be controlling and the conductive losses in the metal shield may be relatively insignificant. It is furthermore possible, for various circumstances of frequency and radius, to alter this optimum condition by varying the index of refraction of the dielectric. In fact, when other sufficiently low loss materials are not available, it may be desirable to use air as a medium. In the latter case, the losses will be almost entirely those contributed by the resistance of the external sheath. According to this plan the medium will be air within the cylindrical metal shell shown in each of Figs. 12, 13 and 14, that is at **56** in Figs. 13 and 14.

Fig. 12 for the metal sheathed dielectric guide corresponds to Fig. 6 for the all dielectric guide. When the lines of force extend to the boundary of the metal sheathed dielectric as in Fig. 12 they end in the metal sheath instead of extending out into surrounding space as for the all dielectric guide of Fig. 6.

The metal sheathed guide has the advantage that it affords immunity from outside inductive influences. The sheath may be extremely thin. A plurality of such sheathed guides may be grouped in a "cable" without appreciable "cross-talk" effects. Reference is made to my application, Serial No. 701,711, filed December 9, 1933, which is directed generally to systems and methods for the transmission of waves through a dielectric guide comprising a metallic sheath.

In connection with Figs. 13 to 24, I will point out how my improved dielectric guide may be utilized to transmit a large amount of signal intelligence requiring a wide frequency range, as for example, a theatre scene transmitted by television. As is well understood, a good television transmission of a scene having considerable detail requires a very wide frequency range. Whatever the range necessary to transmit, for example, a single face, a far wider range is necessary to transmit with as good definition a plurality of faces and other details on a theatre stage. For such a purpose my system is well adapted. The advantage of a wide frequency range may be desirable for a short transmission distance as well as for a long distance; it might be advantageous to employ my invention to transmit a theatre scene to an "annex" in the same or a neighboring city. Using the specific data assigned heretofore in connection with Fig. 1, we assume a carrier current frequency of 1,750 megacycles and its modulation by currents having a frequency band width of 2,000,000 cycles. Probably this is a sufficient band width to give satisfactory television detail for a theatre stage.

Referring to Fig. 13, this shows the proposed television transmitting system in diagrammatic outline. The box **50** represents the apparatus by which the theatre scene is scanned and the varying light impulses from various successive parts of the field of view are converted photo-electrically into currents having components ranging from zero to 2,000,000 cycles, which are then stepped up in frequency to a range from 1,000,000 to 3,000,000 cycles and delivered to the output conductors **51**. The oscillator **52** generates a current of 1,750 megacycles and delivers it over the conductors **53** to the input of the modulator **54**. There the varying photoelectric currents from the conductors **51** are applied to modulate the carrier current of 1,750 megacycles, and the output modulation current comprising the bands from 1,747 to 1,749 megacycles, and 1,751 to 1,753 megacycles and the carrier of 1,750 megacycles are filtered in the band pass filter **54**; and the band from 1,751 to 1,753 megacycles is applied to the coupling unit **55**. This is connected to the proximate end of the composite wave guide, which consists of the cylindrical dielectric core **56** surrounded by the copper sheath **57**. Alternatively, the coupling **55** and the guide **56—57** may be made to serve as the high pass filter by properly proportioning the diameter of the guide in relation to the wave length as will be explained in connection with Figs. 29 and 30. In the latter case it may be desirable to separate the two side bands somewhat more widely than is assumed above. This may be done by a double or triple modulation whereby the final carrier is modulated by say, 11,000,000 to 13,000,000 cycles.

The guide **56—57** of Fig. 13 may be suitably armored or otherwise protected and laid in a conduit. It constitutes a long cylindrical copper container with the dielectric therein, and extends from the transmitting station associated with the source **50** to the receiving station shown in Fig. 14. At the receiving end the guide **56—57** goes into a coupling unit **58**, where the energy of the dielectric waves in the medium **56** is translated into conductive currents in the conductor pair **59**. It will be remembered that these currents comprise a band of from 1,751 to 1,753 megacycles, a modulation side band of frequencies extending over a range of 2,000,000 cycles. At **61** there is a local oscillation generator that generates a current of the carrier frequency that is delivered over the conductor pair **62** to the demodulator **63**. This demodulator **63** also receives the incoming currents on the conductor pair **59**, and the demodulation output product of frequency range from 1,000,000 to 3,000,000 cycles is filtered through and goes to the amplifier **64** and thence to the apparatus **60** where the original band of 0 to 2,000,000 cycles is reproduced. Here these currents are applied to control a beam of light so that it shall vary in correspondence with their variations, and this light beam is distributed over a screen in synchronism with the scanning system at the sending end so that on this screen the whole theatre scene is continuously reproduced.

In Figs. 15 and 16 I have shown apparatus to perform the same functions as the apparatus indicated symbolically by the reference numerals **52**, **54** and **55** in Fig. 13. A three-electrode vacuum tube comprises the glass envelope **70** which is highly evacuated and contains the usual three-electrode arrangement except that the design is carefully adapted for the comparatively high frequencies that are here involved. The plate circuit electrodes **71** are connected with the oscillatory output circuit which comprises the two parallel metal bars **72** connected at their distal ends by the blocking condenser **73**. This blocking condenser consists of interleaved and insulated metallic plates, and it functions to complete the primary circuit for alternating currents of the conductors **72**. The axis of the blocking condenser **73**, that is, the line joining its terminals, is parallel with the intermediate part of the metallic circuit **74**, one terminal of which is connected to the central electrode **75** and the other to the annular electrode **76** on the end of the core **56** of the dielectric guide that comprises this core **56** and the copper shell **57**. The primary currents in the circuit 71—72—73 induce currents in the secondary circuit 74—75—76 and as explained before, lines of force extend in the dielectric material 56 between the electrodes 75 and 76 and are snapped off and propagated as electric waves through the dielectric core 56.

As described thus far, the system of Fig. 15 corresponds to the oscillator 52 of Fig. 13 as if it were feeding directly into the coupling unit 55 of that same figure. In Fig. 17 the circuit connections of Fig. 15 are shown in schematic form and we see how the modulating currents are applied on the conductors 51 to modulate the oscillatory currents set up in the circuit 71—72—73.

An alternative generating system at the sending end is shown in Fig. 18. Here a so-called "electronic oscillator" tube is employed in which the frequency does not depend on the electrical design of an external circuit but rather on certain dimensions and adjustments of and related to the electron paths in the tube itself. Accordingly the intermediate coupling circuit may be omitted and the central electrode 75 on the end of the dielectric guide is connected directly with the grid of the vacuum tube, the annular electrode 76 being connected with the plate of the tube. Thus these electrodes 75 and 76 become integral parts of the oscillator which is enclosed in an extension of the same sheath that surrounds the dielectric guide. This arrangement is such as to avoid as far as possible any electrical discontinuity between the generator tube and the guide.

Yet another generator is shown in Fig. 19 which shows a cylindrical metallic shell that is at the same time a part of the tube envelope and is the plate electrode of the tube. This makes metallic contact with the sheath 57′ of the composite dielectric guide 56—57. The grid 65 is of squirrel-cage type and is connected to the central electrode 75 on the proximate end of the guide. The modulating potential is applied through a separate grid lead 66. The external space to the right of the exciting electrodes 75 and 76 and within the sheath 57′ is filled with a dielectric having the same properties as the wave guide so that there will be a minimum electrical discontinuity between the oscillator and the wave guide. The tube and oscillator in combination are attached to the wave guide either by a bayonet connection or by a threaded union. It is important that there shall be no wave discontinuity at the junction surface of the dielectric material.

At the receiving end the processes are essentially the reverse of those at the transmitting end and therefore they may be performed by the same general type of circuit elements, and it will not be necessary to describe these in much detail. A simple form of receiver is shown in Fig. 20 where 67 is a rectifier or detector. The choke coils 68 permit the passage to the amplifier 69 of only the currents of comparatively low frequency, that is, ranging from 1 to 3 megacycles, and exclude the comparatively high frequency currents around 1,750 megacycles. Of course, the detector 67 should be chosen and designed so that its resistance will match the characteristic impedance of the dielectric guide and prevent the reflection of currents into the guide. This desideratum may be secured by putting the detector unit radially across the electrodes 75 and 76 as shown in Fig. 21, and one or several such units may be employed. In each unit of this detector of Fig. 21 a suitable crystal may be employed, such as zincite, perikon, carborundum, galena or silicon.

When it is not practicable to match impedances in the manner indicated in connection with Fig. 21, an adjustable coupling may be employed as indicated in Fig. 22.

If the carrier current has been suppressed in transmission so that it must be supplied at the receiving end, this may be done as in Fig. 23. Here the oscillation generator of carrier frequency feeds into a short dielectric guide 80 across which is an adjustable iris 81, which provides essentially a metallic diaphragm having an axial aperture of adjustable diameter by which the proper level of local carrier energy may be admitted to the detector.

If the received power is very low, detection may take place in two or more stages with suitable amplification at the lower frequencies, as indicated in Fig. 24.

Of course, there should be a suitable matching of impedances wherever the wave energy is translated from one form or medium to another, as for example, referring to Fig. 2, where the energy of the electric conduction currents in the circuit 32 is translated into the energy of the dielectric displacement currents in the guide D. A suitable impedance match means that energy is transmitted without reflection at the junction, and this may involve a suitable degree of looseness of coupling. If the ring electrodes 34 and 35 are wide with a narrow gap between them, this gives a loose coupling and the reflection is largely of the metallic type. On the other hand, if the rings are narrow and the gap is wide, the coupling is not loose, and the reflection is substantially of dielectric type. What is wanted is such an optimum width of the gap 34—35 that there will be no reflection.

To match impedances in a dielectric guide or with a dielectric guide, and for other purposes, it will be advantageous to know the impedance characteristic of the dielectric guide. The mathematical development given earlier in this specification puts us in position to compute what may be called the impedance characteristic of a dielectric guide. At any point within or without the guide of Figs. 2 and 3, we can get the Poynting vector, which is the vector product of E and H, both of which factors we know from Equations (5) to (10). We integrate the Poynting vector over the cross-sectional area and divide by the square of the effective current (which, of course, is a "displacement current"). Integrating thus and dividing for the internal cross-section of the guide gives a result that may be called the internal characteristic impedance, and similarly for the external cross-sectional area we get the external characteristic impedance. To produce a plot for these impedances we assume the particular value $n=9$, and accordingly in Fig. 25, we have shown a semi-logarithmic diagram of these two impedances, internal and external. The impedance values expressed in ohms are plotted as ordinates against wave lengths in free space as abscissas.

To facilitate matching impedances at the sending end, and to get the proper degree of loose coupling at that place, we may modify the electrodes somewhat from the annular shape as shown at 34 and 35 in Figs. 1 and 2. An alternative construction is shown in Fig. 26. The circular plate shown here has the same diameter as the guide D. Its marginal part 35′ corresponds to the electrode 35 and its central part 34′ to the electrode 34 and the sector-shaped slots 82 correspond to the gap between the electrodes. Comparing with Fig. 2, it will be seen that in Fig. 26 the two conductors 33' of the electric conduction circuit are conductively connected by the radial members 83 lying between the sector-shaped slots 82. By suitable design of the number and size of the slots, an optimum coupling between the conductive circuit and the dielectric guide can be attained.

In any case the dielectric guide, whether provided with a metallic sheath or not, will be suitably protected for overhead suspension or for carrying it in an underground conduit. A lead sheathing may be employed in the case of a metal sheathed guide and the complete guide may be drawn into an ordinary conduit or suspended by rings from a messenger wire. If an all-dielectric guide is employed it may be enveloped in an impervious dielectric covering such as duct cloth or paper impregnated with bakelite.

It is well known that so-called "resistance noise" is one of the factors that sets a limit to the attenuation that is permissible on signaling conductors. Static and other interference also are limiting factors. With my improved all-dielectric guide, so far as electrons are involved in the transmission they are bound electrons, not free as in metals, and for that reason resistance noise will be comparatively low. This advantage will be present to a considerable degree with the metal sheathed dielectric guide, and moreover in that case, static and other interference will be obviated entirely or to a very great extent.

As alternative dielectric materials that may be employed in addition to those mentioned heretofore, there may be mentioned a mixture of paraffin and finely subdivided mica, or rubber with which powdered zinc oxide has been mixed. The latter dielectric material has the advantage of giving a semi-flexible guide and has a low power factor and a favorable dielectric constant lying between the values 6 and 7. The rubber and zinc oxide may be in the proportion of about 35 and 65 per cent respectively. As already pointed out, the dielectric may be either air or vacuum when a metal sheath is used. Such an arrangement would necessarily involve somewhat larger diameters than would otherwise be needed.

In all cases, low conductivity of the dielectric is an important desideratum. In order that the guide be as small as practicable it is desirable also that the material have a high dielectric constant. While water has a high dielectric constant, about 80, it does not have a very low conductivity and hence, on the whole, a medium with lower conductivity than water though with lower dielectric constant, may be preferable. I will mention a few additional dielectrics among which choice may be made of a suitable medium for my improved electric wave guide; these are terpineol, camphor, borneol, halowax, superlowax, rubber, victron and resoglaz.

In electromagnetic wave transmission the lines of electric force and the lines of magnetic force are mutually orthogonal and give what may be called a complete picture of the wave. Such a wave picture suggests the possibility of interchanging the lines of electric and magnetic force. Thus we might have a dielectric guide in which the lines shown in Figs. 6 and 12 are lines of magnetic force and the lines of electric force are coaxial circles. Of course, this would involve an appropriate change of coupling at the ends of the guide to effect the proper translation of energy between the guide and the conduction circuits at its ends.

In still another case the electric and magnetic lines in the dielectric medium may be approximate ellipses or circles or perhaps straight lines that are mutually orthogonal. Instead of annularly disposed electrodes such as 34 and 35 in Fig. 2, one may employ two diametrically opposite electrodes as shown in Fig. 28 or Fig. 33 and in this case the electric waves are polarized in the plane of the axis of the guide and the diameter joining the electrodes. That is, instead of the lines of electric force all being radial they lie somewhat as shown by the transverse continuous lines in Fig. 27, which is a cross-section of the dielectric guide. The corresponding magnetic lines are dotted. In this type of wave the electric and magnetic fields have both transverse and longitudinal components. The lines of electric force, in an all-dielectric guide, form closed loops lying in surfaces parallel with the axis of the guide, one such surface being a diametral plane. In a metal-sheathed guide the loops may still be identified although they are closed through the metal sheath. The magnetic field, in both types of guide, may be represented by closed loops lying in surfaces parallel with the axis of the guide and substantially at right angles to the surfaces in which the lines of electric force lie. By a suitable design of the coupling between the conductive circuit and the guide, the pattern of Fig. 27 can be varied to some extent as may be desired.

By such polarization as in Fig. 27, multiplexing may be accomplished. Thus in Fig. 28 we have a normal system 1 that gives waves with radial lines of force as described heretofore. In addition we have the pair of diametrically opposite electrodes of system 2 that give lines of force like those shown in Fig. 27. These are superposed on the radial lines of system 1. The waves of each system may be modulated independently for multiplexing. Additional waves polarized along a different diameter may be superposed as shown in Fig. 28 for system 3. By employing two sets of electrodes as shown for system 2 and system 3, with their axes at a right angles and energizing them in quarter-phase relation, the waves may be given a rotary polarization and propagated as an advancing rotary field. What I have called system 1 may be multiplexed as explained in connection with Fig. 7.

Another way in which multiplexing may be practiced is to make the guide with an enclosing metal sheath of radius $b$ and with a smaller coaxial sheath of radius $b'$ separating the dielectric into two parts, a central axial part and an annular part. There may be independent wave systems in each part, and obviously the number of inner coaxial shells may be increased so as to have more than two parts.

While a cylindrical cross-section for the guide is obviously preferable for many purposes and is easier for theoretical study and for practical test, other cross-sections may be preferred in some cases. A square or hexagonal cross-section may be easier for assembling the guides in cables, and an elliptical or rectangular cross-section may be preferable when the waves are polarized diametrically in distinction from radially.

It has already been pointed out in connection with Equation (16) that for a given dameter of a dielectric guide there is a limit to the length of wave that can be transmitted therein. Therefore, an abrupt reduction of diameter in a dielectric guide performs a filter function, as may be seen in connection with Fig. 29. That is, suppose waves are being propagated from left to right in the part of the guide of large cross-section and that these waves are composite, comprising various wave lengths up to the limit capable of transmission in a guide of this larger diameter. At the point where the diameter is reduced the waves of longer length will be stopped. The energy of these longer waves may be reflected in the guide, or radiated therefrom, or absorbed in an appropriate resistance, such as the carbon annulus **99** in Fig. 29*a*. But the shorter waves will be transmitted past the junction along the part of the guide of less diameter. Thus we have a high pass filter effect at the junction point.

In Fig. 30 I have shown how my dielectric guide may be interposed in a concentric conductor system to operate as a high pass filter. The concentric conductor system comprises the conductor pair consisting of the cylindrical conductor shell **85** and the axial conductor **86**, with no material between them except air and the necessary spacers. The lines of electric force extend radially between conductors **85** and **86**. Between the points **87** and **88** the outer concentric conductor **85** is enlarged and filled by a dielectric guide **84** with the annular electrodes **96** and **97** at its ends connected respectively with the conductors **86** and **85**. Thus the conduction currents coming from the left to the point **87** are converted into dielectric displacement currents in the guide **84** and their energy is reconverted into conduction currents to go on from the point **88** on the right. But since the wave lengths are limited to a certain ratio to the diameter of the guide **84**, according to Equation (16), only the wave lengths shorter than this limit get through from the left to the right.

Fig. 31 shows a band pass filter interposed in a concentric conductor system. As in Fig. 30, a dielectric guide section is interposed in a concentric conductor system between the points **87** and **88**, and likewise as in Fig. 30, the combination shown in Fig. 31 stops low frequency components. The annular enlargement **101** is bounded by a shell **102** of semi-conductive material, for example, graphite mixed with clay. The longitudinal dimension *g* is adjusted to proper value so that short-length waves, that is, waves of frequency above a certain limit, are diverted into this annular enlargement **101** and their energy is absorbed in the resistance material **102**. Hence the waves that get through from left to right are those lying between lower and upper limiting frequencies, and the device functions as a band pass filter.

Fig. 32 shows a band pass filter that differs from Fig. 31 principally in that instead of the annular enlargement **101** of Fig. 31, this Fig. 32 has a plurality of lateral branch dielectric guide stubs of various suitable diameters, each terminated by a non-reflecting energy-absorbing element. These stubs, so terminated, absorb the shorter waves, permiting only longer waves to go through from left to right. But waves longer than a certain limit will be stopped as explained for Figs. 30 and 31.

Fig. 33 shows a band pass filter in which the electric waves are diametrically polarized. Conduction currents in the conductor pair **103** produce corresponding electromotive forces across the two diametrically opposite electrodes **104** and generate corresponding polarized waves in the dielectric guide section **105**. This has lateral branch dielectric guide stubs which function as explained heretofore in connection with Fig. 32. The incoming currents in the conductor pair **103** on the left may have various frequency components. The low frequencies will be stopped at **87** and the high frequencies will be absorbed in the lateral stubs and only the intermediate band of frequencies will get through on the right. The shell surrounding the dielectric material **105** may be of dielectric material or it may be conductive. Aside from its filter function, this figure shows in simple form a coupling between a conductor pair and a dielectric guide adapted for diametrically polarized waves in the guide.

In connection with the subject-matter of Figs. 29 to 33, reference is made to my U. S. Patent No. 2,106,768, issued February 1, 1938, entitled "Filter system for high frequency electric waves."

Consider a dielectric guide of two parts of different diameter as in Fig. 34. Let it carry waves progressing from left to right that are of a single wave length such that their lines of force are in the form of closed or nearly closed loops in the part of greater diameter (like Case II of Fig. 6), but the lines extend out into adjacent space for the part of less diameter (like Case I of Fig. 6). With propagation from the part of greater diameter to that of less diameter, that is, from left to right, as in Fig. 34, there will be very little radiation from the guide on the left but considerable radiation from the guide on the right. Thus the part of the guide of reduced diameter may be regarded as a radiating antenna and the part of greater diameter as the feeder thereto.

In Fig. 35 the dielectric member is of uniform diameter, and in its non-radiating part it is surrounded by a metallic shell. Here the transmission of energy is as in Case I of Fig. 12. At the transition from the non-radiating part to the radiating part the shell is ended; and in the radiating part the lines of force extend out into the surrounding space as shown in Fig. 35.

In Fig. 36 a directive antenna array is shown based on the principle explained in connection with Figs. 34 and 35. Each of the guides **90**, **91**, **92**, **93** and **94** is fed from below upward with energy of proper wave length and in proper phase relation. From each section of reduced diameter there will be radiation, and in accordance with the known principles of directive antenna arrays, all these foci of radiation lying in a two-dimensional array will give a narrow radio beam. Instead of enlarging the diameter in the non-radiating parts of the antennas, the radiation may be inhibited by surrounding these parts with metallic shells, as explained for Fig. 35.

Note is made here of my pending application, Serial No. 743,753, filed September 12, 1934, in which is further developed and claimed the subject-matter of Figs. 34 to 36.

For demodulation at the receiving end of the guide we may use finely divided carborundum and clay, mixed and baked, for a section of the guide at that end. The current-voltage relation in this substance is non-linear, and this makes it a good modulator for high frequencies. This section of the guide should have its conductivity and dielectric constant chosen at the proper values to make the impedance match the impedance in the adjacent normal part of the dielectric guide. Referring to Fig. 37, the electric waves in the dielectric guide coming from the left meet the disc **77** of distorting or detecting material which, by virtue of its non-linear characteristic gives rise to electromotive forces having frequencies that comprise not only the carrier and side band frequencies, but also twice the carrier frequency plus or minus the side band frequencies. By proper choice of the transmitting frequency or of a locally introduced carrier whose source is not shown in Fig. 37, the desired side bands may be obtained as currents in the coaxial conductor system that extends to the right. In this way we come down, say, from a frequency range in the neighborhood of 1,750 megacycles to a range from 1 to 3 megacycles in the concentric conductor system on the right. These currents are then dealt with in the usual way in wave conductor systems to get the signal indications therefrom. Instead of the carborundum-clay mixture mentioned above, one may use finely divided zinc oxide and clay, mixed and baked, or fused silicon or copper oxide or crystals such as galena or iron pyrites may be used. The moulded materials may be so compounded as to give a wide range of conductivities and effective dielectric constants thereby making it possible for the detecting material used at the terminal to be selected to match the characteristic impedance of the guide.

From the beginning of the practice of electrical signaling, the tendency has been toward the use of wider bands of frequencies. The simple, slow dots and dashes of early telegraphy required but relatively narrow bands of frequencies, but the speed of signaling has increased until now the band of frequencies necessary for transmission taxes the existing facilities, as for instance, in the case of ocean telegraph cables. In telephony there has been a gradual trend toward the use of wider frequency bands in order to attain increased intelligibility and naturalness. In television there has been a corresponding extension of the required frequency band width, and it is recognized by those familiar with the problem that, ultimately, television will require a frequency range yet wider and of the order of one or several million cycles per second. Such a wide frequency range is needed also to enable a plurality of narrow communication bands to be grouped and transmitted together.

My improved system of electromagnetic transmission by means of guided dielectric waves opens the way to transmit on higher frequencies than have been employed commonly heretofore. It is well understood that conductive currents develop the "skin effect" at high frequencies and for this reason and for other reasons, it has not been a common practice to transmit conductive currents effectively at very high frequencies over long distances. Ordinarily such currents have been subject to high attenuation, and for this reason and other reasons their long distance transmission has not been practiced to any great extent.

It is well known that a certain amount of signal intelligence requires a certain frequency band width, whether at high frequency or at low frequency. For example, to transmit a telephone conversation with a certain rather good quality may require a band width of 5,000 cycles. This means a width from 5,000 to 10,000 cycles, or from 95,000 to 100,000 cycles, or from 995,000 to 1,000,000 cycles. The width in frequency range is the same wherever it occurs along the frequency scale. The percentage width is very different in these different cases, being 50 per cent in the case first mentioned, 5 per cent in the next case, and one-half of 1 per cent in the next case.

There are certain transmission difficulties which are more dependent on the percentage width of the band than on its absolute width. In the case assumed in connection with Fig. 1 of the drawings, the absolute width of the frequency band that is transmitted is 2,000,000 cycles. Compared with the frequency ranges commonly considered, this seems like a very wide frequency range, and it is wide in absolute measure. It is 400 times the range that is necessary for a good telephone conversation, and it is about double the whole range for all the various stations and channels of public radio broadcasting in the United States, which is from 550 kilocycles to 1,500 kilocycles. This broadcasting range from 550 kilocycles to 1,500 kilocycles is a range of about 63 per cent, assuming a 100 per cent base at the upper limit of 1,500 kilocycles. But the 2,000,000 cycle range assumed in connection with Fig. 1 is less than 12/100 of 1 per cent compared with the upper limiting frequency of 1,753 megacycles. This indicates the enormous gain in absolute frequency range that may be attained by going to very high frequencies. That is, with very high frequencies one may have an enormously wide frequency range, and a corresponding amount of intelligence may be carried, although that frequency range is small from the percentage standpoint.

In the transmission of intelligence by means of electromagnetic waves, there have been two general methods employed heretofore: (1) by conductive waves along metallic guides, and (2) by radiated displacement waves in free space. The frequencies commonly employed along conductive guides have seldom been greater than 30,000 cycles or something of that order, and, of course, with that limit, the available frequency range for carrying intelligence on one conductive circuit is of no greater magnitude than this 30,000 cycle range. In many cases the frequency range on conductor guides is far less than this, as for example, in the case of long ocean cables where the telegraph speed is only a few hundred words a minute and telephone communication has not yet been practiced. Land wire lines are capable of transmitting wider frequency ranges. The use of loading coils and the use of repeaters are more practicable with land lines than with ocean cables and they are effective in a limited degree to widen the frequency range that can be transmitted over long distances.

For radiated waves in free space, wave lengths have been employed commercially from as long as several kilometers in length, down to as short as of the order of about 4 meters. The longer space waves follow the earth in its curvature, and thus signals may be transmitted by such waves over "non-optical paths," but at the shorter wave lengths mentioned, that is, of the order of 10 meters down to 4 meters or less, the waves will follow a non-optical path imperfectly, or not at all; that is, such short waves will not always bend perfectly around the earth's surface and will go from transmitter to receiver only along a straight or nearly straight line outside the earth's surface. This puts a severe limit on the distance to which they can be transmitted.

As distinguished from systems that employ guided conductive waves and systems that employ radiated displacement current waves, my system involves in some cases guided displacement current waves and in others a combination of guided displacement currents and conductive currents. It is true that antenna arrays have been employed that direct the waves of displacement current in free space, but that involves an initial directing of the wave, and does not involve any guiding of them as occurs in connection with conductive waves along metallic conductors.

By my invention it becomes possible to employ displacement current waves guided along dielectric guides, and thus to go to high frequencies with their corresponding favorable band widths.

The propagation of waves along dielectric guides appears to be sui generis in the realm of electromagnetic wave transmission and readily distinguishable from other forms of guided wave propagation. Comparison of dielectric guide systems with other systems for guiding electromagnetic waves may serve to emphasize some of the distinguishing features. In some cases the nature of the structure along which the waves are guided is itself the salient feature of differentiation; in other cases the guiding structures may be identical and the nature, characteristics and behavior of the guided electromagnetic waves must be looked to. In most cases, both the guiding structure and the waves will be seen to be essentially different.

Thus, dielectric guide systems may be contrasted with ordinary conduction current systems utilizing as the guiding structure a pair of metallic wires, shielded or unshielded, or a pair of coaxial conductors. Considering first the nature of the guiding structure, it will be apparent that no structure falls in the category of conduction current systems that does not provide two or more conducting members suitable for the go-and-return flow of conduction current. There can be no confusion therefore between conduction current systems on the one hand and such typical dielectric guides, on the other hand, as consist wholly of dielectric material or of dielectric material with a single metallic core or of a single metallic pipe containing only a dielectric medium. A dielectric guide, however, may comprise a plurality of metallic conductors, and where it comprises, for example, both a metallic sheath and a metallic core, as disclosed in this specification, the structure is essentially the same as that of a coaxial pair, and if the one system is to be distinguished from the other the nature, characteristics, etc., of the waves guided along the structure must be examined.

In the ordinary coaxial conductor transmission system, as in all conduction current systems, the go-and-return flow of conduction currents is an essential and significant feature. In a dielectric guide system such current flow may be absent or there may be conduction current in only one conductor of the guide, e. g., in a metallic sheath. In the conduction current system again there is no component of either the electhric or magnetic field that lies in the direction of wave propagation, excepting, of course, to take account of the trailing of the wave front in the vicinity of imperfect conductors, this trailing representing a flow of energy into the conductors equal to the energy loss occurring therein. In all of the dielectrically guided waves herein disclosed, on the contrary, either the electric field or the magnetic field has a substantial component in the direction of wave propagation, entirely independent of energy loss in metallic elements, this longitudinal component, in all of them too, being evident in a longitudinal flow of magnetic current or of displacement current through fairly well defined regions within the dielectric medium.

In other respects, too, the dielectrically guided waves herein disclosed differ radically from the waves associated with ordinary conductor systems. The velocity at which they are propagated along the guide, and therefore the wave-length within the guide, depends in a marked degree on a transverse dimension of the guide. The diameter is the significant dimension in the case of a simple cylindrical guide. This characteristic is in strong contrast with ordinary conductor systems, where the velocity and wave-length are substantially independent of the transverse dimensions.

Another striking characteristic of the waves herein described is the existence of a cut-off frequency separating a high frequency range of easy transmission from a lower frequency range of zero or negligible transmission. The frequency at which this cut-off occurs depends on a number of factors, such as the field pattern of the wave, the dielectric constant of the medium, and a transverse dimension of the guiding structure. Regardless of the factors involved, however, it is true that for any particular guide and type of dielectrically guided wave herein disclosed this anomolous behavior of the attenuation-frequency characteristic may be observed.

Electromagnetic waves of optical frequencies have been propagated within quartz rods and within polished tubes, but this involves a manner of transmission entirely distinct from that of a dielectric guide system. There are myriads of independent waves, each arising from an atom within an incandescent source, and all are in random frequency and phase relation. Each wave progresses along optical paths and is confined, not guided, within the dielectric medium by repeated internal reflection from the dielectric or metallic surfaces. Such waves have none of the important characteristics, hereinbefore described, that are generally attributable to dielectrically guided waves.

From the foregoing comparisons it is evident that the novel waves described in this application are essentially different from any waves heretofore known and used, as different in fact as radio waves and ordinary conduction currents differ from each other. It may well be, however, that the specific forms of waves herein disclosed are only representative of a broader class of waves, the limits or boundaries of which are yet to be accurately fixed, and it is impossible at this time to predict what feature or features of the several herein discussed might be found to be the common link between them all. The term "dielectrically guided" as used in the appended claims, therefore, is intended to embrace the various novel waves so denominated in this specification and such other waves as may fairly be found equivalent thereto.

By "dielectric guide" is to be understood any wave-guiding structure capable of sustaining dielectrically guided waves. All such guides appear to be characterized in that they comprise a dielectric medium having an enclosing boundary defining a discontinuity in electrical properties.

What is claimed is:

1. The method of transmitting electromagnetic effects which comprises applying electromagnetic waves to a dielectric guide and propagating these waves along said guide with the energy flow largely in the one direction of propagation and deriving the power available within the guide at some other point along the guide, the propagation being characterized by a critical existence relation between the frequency of said waves, a transverse dimension of said guide and

the index of refraction of the dielectric medium comprising said guide.

2. The method of transmission which comprises applying electromagnetic waves to a dielectric guide, dielectrically guiding the waves along said guide with the wave energy largely confined within the guide, and at some other point along said guide withdrawing in substantial proportion the transmitted wave energy there available.

3. The method of transmitting energy from one place to another which comprises applying high frequency electromagnetic waves to a wave guide comprising a dielectric medium, propagating these waves along said guide with the energy flow largely from said one place to the other place, and at said other place abstracting from said guide at least the greater part of the wave energy there available, the propagation of said waves being characterized in this that the phase velocity is substantially different than that of light in said dielectric medium.

4. The method of transmitting energy from one place to another which comprises applying high frequency electromagnetic waves to a wave guide comprising a dielectric medium, propagating these waves along said guide with the energy flow largely from said one place to the other place, and at said other place abstracting from said guide substantially all of the wave energy there available, the propagation of said waves being characterized in this that the frequency of said waves exceeds a certain frequency related to the physical constants of the guide, below which said waves are highly attenuated.

5. The method of transmitting energy from one place to another which comprises applying high frequency electromagnetic waves to a wave guide comprising a dielectric medium, propagating these waves along said guide with the energy flow largely from said one place to the other place, and at said other place abstracting from said guide in substantial proportion the wave energy there available, the propagation of said waves being characterized in this that the length of said waves within the guide is substantially dependent on a transverse dimension of said guide.

6. The method of transmitting energy from one place to another which comprises applying high frequency electromagnetic waves to a wave guide comprising a dielectric medium, propagating these waves along said guide with the energy flow largely from said one place to the other place, and at said other place abstracting from said guide at least the greater part of the wave energy there available, the propagation of said waves being characterized by the longitudinal flow of current in longitudinal paths wholly within said dielectric medium.

7. The method in accordance with claim 3 in which the propagation of said waves is additionally characterized in this that there is a critical frequency, determined at least in part by a transverse dimension of said guide and the index of refraction of said dielectric medium, separating a range of easy transmission and a range of zero or negligible transmission, and the length of said waves within the guide is determined at least in part by a transverse dimension of said guide.

8. In the transmission of signals by means of a dielectric guide of small and compact cross-section, the method steps which comprise generating and propagating in said guide electromagnetic waves of a character such that they subsist only above a certain cut-off frequency, modulating said waves with the signals to be transmitted and utilizing the said waves after transmission within the guide, said waves having a suitable moderate length compared to a transverse dimension of said guide so that the lines of electric force of the waves will lie principally within the guide.

9. A system for the transmission of intelligence from one place to another comprising a dielectric guide extending between the two places, means at the one place for applying to said guide for propagation thereover electromagnetic waves modulated in accordance with the intelligence to be transmitted, and means at the other place for receiving said waves and deriving the intelligence therefrom, said propagation being characterized in that it is possible only at frequencies above a critical frequency related to a transverse dimension of said guide, and further in that the velocity of propagation is substantially dependent on a transverse dimension of said guide.

10. The method of communicating electrical effects from one place to a widely separated place which comprises generating high frequency displacement current waves at the one place, dielectrically guiding said waves to the other place in a wave guide comprising a suitable medium of restricted cross-section with the energy flow substantially in the one direction of transmission, and receiving them in said guide at said other place.

11. Apparatus for transmitting intelligence electrically from one place to another comprising a dielectric guide of limited cross-section extending between the two places, means at the one place to generate dielectrically guided waves in the guide, means to impress on said waves the intelligence to be transmitted, and means at the other place to receive said waves within the guide and to derive the transmitted intelligence therefrom.

12. A system for the transmission of intelligence between two places comprising a dielectric guide extending between said places, means for generating intelligence-bearing high frequency currents, a terminal structure at one of said places for generating corresponding dielectrically guided waves in said guide, and means at the other of said places for receiving the waves within the guide and deriving from them the intelligence transmitted, said dielectrically guided waves being characterized in one or more of the following respects: (*a*) the velocity of transmission is different from that of light in the dielectric medium comprising the guide, (*b*) propagation occurs only at a frequency exceeding a certain frequency determined by the physical constants of said guide, (*c*) the length of the waves within the guide is dependent on a transverse dimension of said guide.

13. In the transmission of dielectrically guided waves along a dielectric guide, the method steps which comprise establishing the length of the waves in relation to the transverse dimensions of the guide so that the lines of force of the waves will be principally closed loops within the guide and withdrawing at one point substantially all of the energy of said waves transmitted within said guide for application to a useful load.

14. In combination, a dielectric guide, means for establishing therein progressive electromagnetic waves characterized in that at least one

of the field components, electric and magnetic, has a substantial intensity component in the direction of wave propagation, means for impressing signals on said waves, receiving means within said guide for converting said waves into equivalent conduction currents, and means for deriving said signals from said conduction currents.

15. In a system for communicating intelligence from one place to another place, an electromagnetic wave guide extending between said places comprising a dielectric medium of restricted cross section, the boundary of which separates it from a medium of substantially different electromagnetic characteristics, means for launching electromagnetic waves in said guide at said one place comprising a terminal structure for said guide and a source of waves connected thereto, said source of waves being adapted to operate at a frequency higher than a critical frequency only above which waves of the character developed by said terminal structure are readily transmitted through said guide, means for impressing on said waves the intelligence to be communicated, and at the other place, means including a terminal structure for said guide for receiving the waves transmitted through said guide and deriving the said intelligence therefrom.

16. In combination, a transmission structure comprising a dielectric bounded laterally by a discontinuity and means for establishing therein high frequency dielectrically guided electromagnetic waves of a type having a substantial longitudinal component of magnetic intensity.

17. In combination, a dielectric guide and means for establishing therein asymmetrically polarized dielectrically guided high frequency electromagnetic waves.

18. In combination, a wave guide, means for transmitting therethrough high frequency electromagnetic waves in which at least one of the two component fields has one intensity component parallel with the axis of the guide and another intensity component transverse to the axis of the guide and in an axial plane, and means remote from said transmitting means for withdrawing from said guide in substantial proportion the energy transmitted by said waves.

19. In combination, a wave guide having a continuous boundary enclosing a dielectric medium and means for generating in said guide for progressive transmission therethrough high frequency electromagnetic waves of a kind such that there is a continuous longitudinal flow of magnetic current in certain regions within said guide and a similar longitudinal return flow in other regions.

20. A combination in accordance with the claim next preceding in which said waves are further characterized in that the velocity of propagation differs from that of light in the medium and is substantially dependent on a transverse dimension of said guide.

21. In combination, a wave guide and means for generating therein and propagating therethrough electromagnetic waves characterized in that the lines of magnetic force form closed loops lying substantially parallel to the axis of the guide.

22. A combination in accordance with the claim next preceding in which some of said loops of magnetic force lie in a plane containing the axis of said guide.

23. Apparatus for signaling between two places comprising a dielectric guide extending between them, said guide comprising a substance of substantially greater dielectric constant than air and of low conductivity, means at one of said places for generating high frequency electromagnetic waves of lengths measurable in millimeters for dielectrically guided transmission into and along said guide, means at the same place for modulating such waves in accordance with signals to be transmitted, and means at the other place for receiving and demodulating the waves to get the corresponding signals.

24. The method of signaling from one place to another place which consists in generating high frequency dielectrically guided waves in a medium of high dielectric constant extending between the two places, confining and transmitting the waves therein, modulating them by signals at one of said places, and demodulating them to reproduce the signals at the other place.

25. In combination, means for generating a high frequency electric conduction current, means for modulating said current with a frequency band of currents of great absolute width and small percentage width, a dielectric guide, and means to generate displacement current waves in one end of said guide corresponding to the modulated high frequency conduction current, the transmission of said waves through said guide being controlled by a critical existence relation between the frequency of said waves, a transverse dimension of said guide and the refractive index of the dielectric medium comprising said guide.

26. In combination, means for generating cyclic electromagnetic impulses of frequency of the order of 1750 megacycles per second, a wave guide for the transmission of corresponding dielectrically guided waves, and impedance matching means for imparting said impulses from the said generating means to the said guide.

27. Apparatus for signaling between two places comprising a dielectric guide extending between them, said guide consisting essentially of a substance of considerably greater dielectric constant than air, means at one of said places for generating high frequency electromagnetic waves for dielectrically guided transmission into and along said guide, means at the same place for modulating such waves in accordance with signals to be transmitted and means at the other place for receiving and demodulating the waves to get the corresponding signals.

28. As a means for communicating electrical effects from one place exclusively to one other place or to a limited number of other places, an extended body of dielectric extending from the one place to the other place or places and bounded laterally by a dielectric discontinuity, means to generate dielectrically guided waves of sufficiently high frequency therein at the one place and to propagate them therein to the other place or places, and to such place or places only, and means at said other place or places for receiving said waves.

29. A system for transmitting electrical effects between separated points comprising an elongated transmission structure extending between said points consisting essentially of a wave sustaining medium bounded by an electromagnetic discontinuity, means at one of said points for applying to said structure electromagnetic waves of such frequency and character as to be guided by and largely confined within said discontinuity, and means at the other of said points for receiving in substantial proportion the energy of the waves transmitted within said structure.

30. A system for transmitting signals over long

distances comprising a uniform, non-rectilinear, cylindrical electromagnetic wave guide bounded laterally by a dielectric discontinuity, means for applying at one end of said guide electromagnetic waves of field pattern and frequency adapted for propagation through said guide, said waves being modulated in accordance with complex signal waves occupying a wide frequency range and most of the energy of said modulated waves being confined within said guide, and means at the other end of said guide for receiving and demodulating the said waves propagated within said guide.

31. A multiplex system for the transmission of signals between separated points comprising a wave guide extending between said points, said guide consisting essentially of a dielectric medium bounded by a discontinuity in electrical properties, means at one of said points for applying to said guide signal-modulated electromagnetic waves of one characteristic field pattern and differently signal-modulated electromagnetic waves of another characteristic field pattern, and means at the other of said points for discriminately affecting said waves of different field patterns.

32. The method of utilizing an electromagnetic wave sustaining medium, elongated and bounded by a discontinuity, which comprises concurrently establishing within said medium a signal-modulated polarized electromagnetic wave adapted for dielectrically guided propagation through said medium, and another electromagnetic wave, differently signal-modulated and polarized.

33. The method of operation with a wave guide which comprises propagating through said guide two dielectrically guided waves that are differently signal-modulated and of different characteristic field patterns, and selectively receiving the two waves so propagated.

34. The method of operation with a dielectric guide which comprises establishing in said guide two dielectrically guided waves of asymmetric type having different planes of polarization, transmitting said waves concurrently through said dielectric guide and concurrently receiving them.

35. The method in accordance with the claim next preceding which both of said waves are of the asymmetric magnetic type.

36. The method of multiplex operation with a wave guide which comprises generating two signal-modulated high frequency waves, applying said waves to said guide and propagating them thereover in respective different electromagnetic forms, one of said forms being characterized by a circular field component coaxial with said guide and the other by a diametral field component, both of said forms being such that propagation through said guide takes place only at frequencies above a critical high frequency.

37. Means for generating multiplex waves in a dielectric guide consisting of a central electrode and a plurality of annular electrodes at one end of the guide, a plurality of conductive circuits connected with different sets of these electrodes and means for energizing these circuits at high frequencies above the cut-off frequency of said guide such that the corresponding wavelengths will be of the same order of magnitude as the transverse dimensions of the guide.

38. Means for producing two sets of diametrically polarized electromagnetic waves in a dielectric guide comprising two pairs of electrodes at the ends of respective differently directed diameters, and electric circuits for energizing the respective sets of said electrodes.

39. A dielectric guide having central and annular electrodes at its end for the development of radially polarized waves in the guide, and in combination therewith electrodes at the ends of a diameter of the guide for generating superposed diametrically polarized waves in the guide, and respective sources of differently modulated waves connected to the two sets of said electrodes.

40. A dielectric guide and means for generating elliptically polarized waves for transmission therein comprising two pairs of electrodes at ends of respective differently directed diameters, respective circuits for said electrodes and means to energize said electrodes over said circuits at the same frequency and in proper phase relation to generate said waves.

41. In combination, means for generating cyclic electromagnetic impulses of high frequency, a dielectric guide for the distance transmission of corresponding dielectrically guided waves, an amplifying repeater interposed in said guide, means for converting said dielectrically guided waves into a form suitable for application to said repeater and means for converting the waves amplified by said repeater into a form suitable for application to said dielectric guide.

42. In combination, an electric conduction circuit, means for generating cyclic electromagnetic currents of high frequency therein, a dielectric guide for the transmission of corresponding electromagnetic waves of a character such that transmission is controlled by a critical existence relation between the frequency of said waves and a transverse dimension of said guide, and an amplifying repeater interposed across said guide, said repeater comprising frequency-step-down apparatus on one side and frequency-step-up apparatus on the other side with an amplifier between them.

43. In combination, a wave guide, means for propagating intelligence-bearing electromagnetic waves through said guide, a conduction current circuit in the path of said waves within said guide for deriving an electromotive force therefrom, and means responsive to said electromotive force for deriving said intelligence, said waves being of such character that the velocity of propagation is a function of a transverse dimension of said guide and there is a cut-off frequency defining the lower limit of the propagation range.

44. In combination in a signalling system, a wave guide, means for propagating dielectrically guided waves therethrough, means for modulating said waves with a signal to be transmitted, and receiving means within said guide for deriving from said waves an electromotive force varying in intensity in accordance with the instantaneous amplitude of said waves.

45. In combination, a wave guide, means for applying to said guide electromagnetic waves for dielectrically guided transmission therethrough and a conduction current receiving circuit structure in which the dimensions transverse to lines of the electric field are small compared with the wave-length of the guided waves received.

46. In combination, a conductive circuit, a dielectric guide, and an impedance matching coupling between them for interconverting currents in said circuit and dielectrically guided waves in said guide.

47. In combination, a set of metallic conductors, means to generate high frequency conduction currents therein, a wave guide and a nonreflecting coupling between said conductors and said guide adapted at a sufficiently high fre-

quency to convert the energy of the currents in said conductors into the form of displacement current waves in said guide, said frequency being high enough so that the corresponding wave-length will be of the same order of length as the transverse dimensions of the guide, and said waves being of such character that propagation through said guide takes place only at frequencies above a critical frequency related to a transverse dimension of said guide.

48. In combination, a dielectric guide, means to send dielectrically guided waves therein at a frequency such that the corresponding wave-length will be of the same order as the transverse dimensions of the guide, receiving apparatus comprising a metallic conductor circuit, and a non-reflecting coupling between said guide and said circuit adapted to receive the energy of the waves in the guide and convert such energy into the form of conduction currents in said circuit.

49. In combination, a metallic conductor system, a dielectric guide, and a substantially non-reflecting coupling between said conductor system and said guide adapted to convert energy in the form of conduction currents in said conductor system and in the form of dielectrically guided waves in said guide from one form to the other.

50. In combination, a set of metallic conductors, means to generate high frequency conduction currents therein, a dielectric guide and a non-reflecting coupling between said conductors and said guide, the transverse dimensions of said guide being comparably related to the wave-length at the said frequency so that the lines of electric force from said conductors at said coupling will extend therefrom into said guide and become detached and propagated therein as displacement current waves.

51. In combination, a wave guide consisting essentially of a dielectric medium the outer boundary of which separates said medium from another medium having unlike electromagnetic properties, and means for establishing signal-modulated progressive electromagnetic waves in the said guide comprising a pair of terminals insulated from each other and contiguous with said dielectric medium, and connections from said terminals to a signal-modulated wave source the frequency of which is greater than the cut-off frequency of said guide.

52. The method of operating with a dielectric guide which comprises establishing lines of electric force terminating on circuit elements lying at or within the periphery of said guide, and varying the intensity of said electric lines of force at a high frequency so related to a transverse dimension of said guide that said lines of force become detached from said elements and are propagated as progressive waves through said guide.

53. The method of communicating electric waves into a dielectric guide from a conductive circuit which consists in generating lines of force in said guide with their ends terminating within said guide on electrodes of the said conductive circuit and alternating the current in said conductive circuit so rapidly that the lines of force are detached in closed loops and propagated within the said guide substantially without reflection of energy from said guide back to said conductive circuit.

54. In combination, a conductor pair, a dielectric guide, and a pair of electrodes adjacent to said guide and connected respectively with the conductors of said pair, said electrodes being spaced to match the impedances of said pair and said guide.

55. In combination with a dielectric guide, a pair of electrodes diametrally spaced with reference to said guide, and a source of waves connected to said electrodes of such high frequency that dielectrically guided waves are generated within said guide.

56. In a system comprising a wave guide carrying high frequency electromagnetic waves of a character such that the velocity of propagation is substantially dependent on a transverse dimension of the guide, a pair of conductive members disposed on opposite sides of the axis of said guide and a circuit connected to said members, whereby said guide and circuit are connected in energy transfer relation.

57. A wave guide characterized by a lateral boundary enclosing only a dielectric medium and a circuit associated with said guide, said circuit being completed through a current path extending through said dielectric medium transversely to the axis thereof and from one side thereof to the other, whereby there may be energy transfer between progressive electromagnetic waves in said guide and high frequency currents in said circuit.

58. Means for producing diametrically polarized waves for signaling along a dielectric guide comprising electrodes at the opposite ends of a diameter of such guide and means for energizing said electrodes at high frequency to generate such waves in the guide.

59. In combination in a system utilizing dielectrically guided waves, a dielectric guide for carrying said waves, a metallic circuit and means coupling said guide and circuit in energy transfer relation comprising a pair of concentric electrodes spaced apart and disposed in contiguity with the dielectric medium comprising said guide.

60. In combination, a cylindrical wave guide, a central electrode at one end thereof, a concentric peripheral electrode at the same end and means to generate an alternating electromotive force across said electrodes at a frequency above the cut-off frequency of said guide for symmetric electric dielectrically guided waves whereby such waves are established in said guide.

61. In combination, a cylindrical dielectric guide, a central disc electrode at its end, an annular electrode at the same end of the guide spaced radially from the said disc electrode, and means to generate an alternating electromotive force across said electrodes at a frequency high enough for the generation and progagation of dielectrically guided waves along the said guide.

62. In combination, a metallic conductor circuit, a dielectric guide and a coupling between them, said coupling comprising a central electrode adjacent to one end of the guide and connected to one conductor of said circuit, and an annular electrode also adjacent to the same end of the guide and connected to the other conductor of the circuit, said central and annular electrodes having an annular space between them of such width as to minimize substantially reflection losses in the interchange of dielectrically guided waves in said guide and currents in said conductor circuit.

63. Means for generating electromagnetic waves in a dielectric guide in the form of closed loops lying in radial planes of the guide comprising central and annular electrodes at the end of the guide and means for charging them oppo-

sitely in alternation at very high frequency, said electrodes being so proportioned as substantially to minimize reflection losses.

64. The method of signaling over a dielectric guide which consists in generating high frequency electromagnetic waves at one end, transmitting them along the guide, and at the other end applying these waves so that their lines of magnetic force in the guide will cut a non-linear conductor and thereby develop comparatively low frequency electric currents in a conductive circuit comprising said non-linear conductor, said waves being of such character that a cut-off phenomenon appears in the attenuation-frequency relation.

65. Means for receiving electromagnetic waves transmitted in a dielectric guide comprising central and annular electrodes at the receiving end of such guide, an asymmetric resistance connected across the gap between said electrodes and a receiving circuit in shunt to said asymmetric resistance.

66. In combination, a dielectric guide carrying electromagnetic waves of certain frequencies, receiving apparatus associated with one end thereof and comprising central and annular electrodes, and means for demodulating the energy of received electromagnetic waves on the guide consisting of a guide section interposed between the end of the guide and the electrodes, said guide section being of material having a nonlinear characteristic, whereby desired modulation components of other frequency are received.

67. In combination, a dielectric guide for transmission of electromagnetic waves along its length, said transmission being characterized by a critical existence frequency, and means across the guide to reduce the volume of energy of the waves transmitted past it within the guide, said means being proportioned to establish a desired energy ratio between the waves on its output side and those on its input side.

68. A combination in accordance with claim 67 in which said means to reduce the volume of energy comprises a diaphragm having an opening therein.

69. In combination, a wave guide, means for propagating dielectrically guided waves through said guide, and an adjustable iris across said guide whereby said waves in the guide may have their intensity adjustably controlled in transmission through said iris.

70. In combination, a dielectric guide, means at one end thereof to generate high frequency electric displacement currents in the guide for dielectrically guided propagation therein, and adjustable means across the guide to control the volume of wave energy flow past such means.

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