April 30, 1940. S. A. SCHELKUNOFF 2,199,083

TRANSMISSION OF GUIDED WAVES

Filed Sept. 4, 1937

FIG. 1

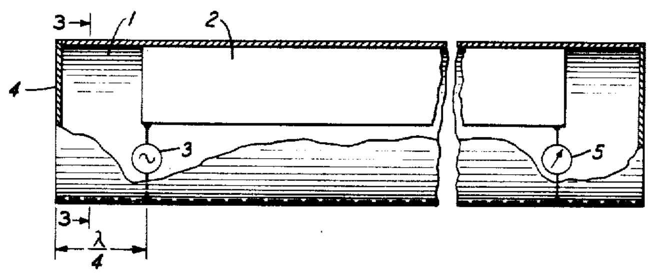


FIG. 2

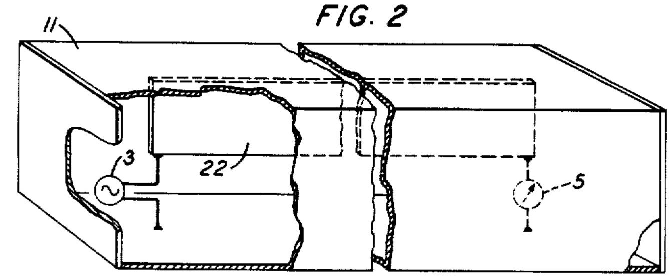


FIG. 3

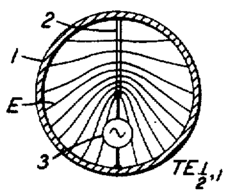


FIG. 4

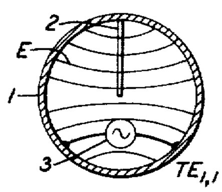


FIG. 5

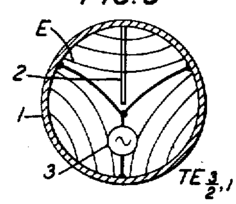


FIG. 6

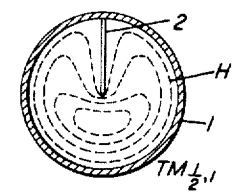


FIG. 7

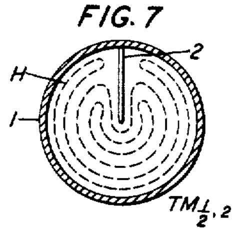


FIG. 8

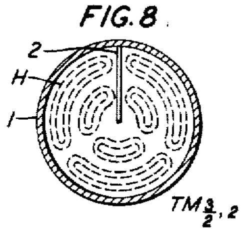


FIG. 9

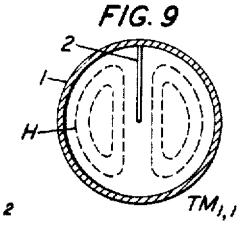


FIG. 10

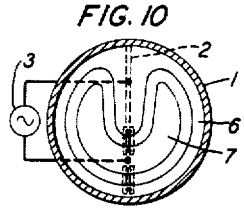


FIG. 11

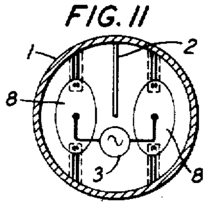


FIG. 12

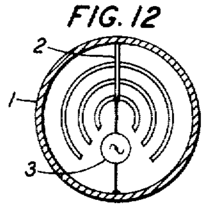
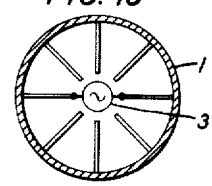


FIG. 13



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2,199,083

TRANSMISSION OF GUIDED WAVES

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Application September 4, 1937, Serial No. 162,422

16 Claims. (Cl. 178—44)

This invention relates to high frequency electromagnetic wave transmission systems and more particularly to the guided transmission of hyperfrequency electromagnetic waves.

In my copending application Serial No. 56,959, filed December 31, 1935, which issued on February 21, 1939, as U. S. Patent No. 2,147,717, it is shown that electromagnetic waves of certain kinds can be guided through a metallic pipe containing only a dielectric medium. Guided transmission of this kind is possible only at frequencies exceeding a critical or absolute cut-off frequency that is dependent on the transverse dimensions of the guiding structure, the guide thus presenting the characteristics of a high-pass filter. There are many types of such waves, each distinguished by its characteristic field pattern, and for each type there is a corresponding critical frequency, generally higher than the absolute cut-off frequency, which must be exceeded if a wave of that particular type is to be propagated within the guide. There is only one type of wave that can be propagated within the guide at frequencies so low as to approximate the absolute cut-off frequency, but at frequencies above the next higher critical frequency, not only a wave of this type but also one or more independent waves of different type, travelling at different velocities, will originate at the transmitter unless special precautions are taken to prevent it.

A principal object of the present invention is to provide a guided wave system of the kind described in which the absolute cut-off frequency, or minimum frequency of transmission, is substantially lowered without increasing the overall dimensions of the guide. Another object is to increase the frequency range over which the guide will transmit but a single type of guided wave.

The present invention in one of its simplest embodiments comprises a hollow copper tube having a longitudinal copper fin or baffle extending radially inward from the periphery of the tube, together with means for launching electromagnetic waves of suitable character in the tube. The foregoing embodiment is typical and illustrative only, however, and the nature of the present invention and its various objects, features and advantages will appear more fully in the detailed description that is to follow. Reference will be made to the accompanying drawing, in which:

Figs. 1 and 2 illustrate typical transmission systems embodying the present invention;

Figs. 3 to 11 represent schematically various possible types of electromagnetic waves that may be propagated in one form of guide in accordance with the invention; and

Figs. 12 and 13 illustrate two other embodiments of the invention.

The various types of electromagnetic waves that can be guided through a metallic pipe may be classified as explained in my copending application, supra, into two groups, transverse magnetic (TM) and transverse electric (TE), the former comprising those waves that are characterized by the fact that the vector H representing the magnetic component of the field is wholly transverse to the direction of propagation and the latter comprising such waves as are characterized in that it is the electric vector E that lies wholly transverse to the direction of propagation. Transverse magnetic waves can be described by means of characteristic distributions of electrical potential over any particular cross-section of the guide and transverse electric waves by means of similar distributions of magnetic potential over any particular cross-section. If x and y are the Cartesian coordinates of a typical point in a given cross-section, the functions T (x, y) governing the potential distribution satisfies the following equation:

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}=-\chi^2 T \qquad (1)$$

where χ is a positive real constant depending upon the size and shape of the pipe and upon the particular characteristic field distribution of the wave to be transmitted. For transverse magnetic waves, T is also proportional to the longitudinal electric displacement current density, while for transverse electric waves T is proportional to the longitudinal magnetic displacement current density.

The various possible characteristic field distributions are in accord with those solutions of Equation 1 which satisfy appropriate boundary conditions on the surface of the pipe. Either T or its normal derivative must vanish on the boundary, depending upon whether the wave is transverse magnetic or transverse electric, respectively.

Transmission of energy can take place only if the frequency is higher than a critical frequency depending upon χ. This cut-off frequency may be derived from the equation $\omega=2\pi f=\chi c$, where c is the velocity characteristic of light in the dielectric medium within the pipe; the corresponding wave-length is

$$\frac{2\pi}{\chi}$$

If the space within the pipe is simply connected, χ is always greater than zero and there exists a lower frequency limit below which there is no transmission mode capable of transferring energy along the tube.

Equation 1 happens to be also the equation for the displacement of an oscillating elastic membrane, and the different transmission modes for electromagnetic waves can, with mathematical exactitude, be associated with characteristic vibrations of the membrane representing the cross-section of the pipe. The boundary condition established by the presence of the metallic pipe in the case of transverse magnetic waves, viz., that longitudinal electric intensity must vanish at the periphery of the pipe corresponds mathematically with the boundary condition established by fixing the edge of the oscillating membrane. Similarly, in the case of transverse electric waves the boundary condition established by the presence of the metallic pipe, viz., that longitudinal magnetic intensity must vanish at the periphery of the pipe corresponds mathematically with the boundary condition of a free-edged oscillating membrane. In brief, the edge of the membrane is to be considered fixed or free, depending on whether the corresponding waves are transverse magnetic or transverse electric. The cut-off frequencies for the electromagnetic waves are proportional to the natural frequencies of the corresponding membranes. This fact is helpful in obtaining a qualitative idea of the relationship between various cut-off frequencies.

It has been observed by Lord Rayleigh with reference to oscillating membranes that each new constraint raises the gravest natural frequency of the membrane and that conversely a removal of a constraint results in lowering the gravest natural frequency. The same observation, applicant has found, may be made with reference to guided electromagnetic waves. Thus, if a metallic sheet is disposed longitudinally in a tubular metallic pipe carrying transverse magnetic waves so that it extends radially inward from the periphery of the pipe, it, as well as the pipe itself, imposes a constraint on the waves, just as clamping a circular membrane along a radius would impose a constraint on the mode of vibration of the membrane. Accordingly, the lowest cut-off frequency for transverse magnetic waves will be raised. On the other hand, if the pipe carries transverse electric waves the radial sheet removes a constraint, just as cutting the corresponding circular membrane from periphery to center would do, and both the pipe wall and the radial sheet establish free-edge boundary conditions. Accordingly, the lowest cut-off frequency for transverse electric waves will be lowered.

When the metal partition extends from the axis of the tube to its periphery, the proper values for χ can easily be calculated. Thus in polar coordinates the potential distribution is given by

$$T(\rho,\varphi)=J_p(\chi\rho)\sin p\varphi, \text{ or } T(\rho,\varphi)=J_p(\chi\rho)\cos p\varphi \tag{2}$$

where φ is measured from the partition.

If the wave is transverse magnetic, then $T(\rho,0)$ and $T(\rho,2\pi)$ must vanish. Consequently, we must choose the first form in (2) and let

$$\sin 2p\pi=0,\ 2p\pi=n\pi,\ p=\frac{n}{2},\ n=1, 2, 3, \ldots \tag{3}$$

Likewise, T must vanish on the boundary $\rho=a$ of the tube; thus

$$J_{\frac{n}{2}}(\chi a)=0 \tag{4}$$

The smallest root of this equation corresponds to $n=1$; it is

$$\chi a=\pi \tag{5}$$

The corresponding cut-off is given by

$$\omega_c=\frac{\pi c}{a} \text{ and } \lambda_c=2a$$

If the wave is transverse electric, then the normal derivative of T must vanish on two sides of the partition and on the periphery. Hence, T must be given by the second form in (2) and χa must be a root of

$$J'_{\frac{n}{2}}(\chi a)=0 \tag{6}$$

The smallest root occurs when $n=1$ and (6) becomes

$$J'_{\frac{1}{2}}(\chi a)=0 \text{ or } \frac{\tan \chi a}{\chi a}=2 \tag{7}$$

Approximately we have

$$\chi a=1.16,\ \lambda_c=\frac{2\pi a}{1.16} \tag{8}$$

In the absence of a partition the lowest cut-off frequency for transverse electric waves in a tubular metallic guide is that for the so-called $TE_{1,1}$ (or $H_{1,1}$) wave, and it corresponds to $\chi a=1.84$, whereas with the partition the corresponding figure for χa is 1.16. Thus, the radial partition results in lowering the absolute cut-off frequency by almost 37 per cent. For transverse magnetic waves, on the other hand, the lowest cut-off frequency in the absence of a partition corresponds to $\chi a=2.40$ whereas with the partition the corresponding figure is 3.14. Thus, for transverse magnetic waves the lowest cut-off frequency is raised by nearly 31 per cent. An important consequence is that the frequency range between the absolute cut-off frequency and the next higher critical frequency is substantially widened.

Referring now to Fig. 1 there is shown an embodiment of the present invention comprising a metallic tube 1, a radially disposed metallic baffle 2 extending longitudinally through the tube, and the wave source 3 connected between the axial edge of the baffle 2 and the opposite point of the tube wall. The end of the tube 1 is closed by a metallic reflector 4 which may be in the form of a copper disc and which is disposed at such distance from the connecting leads associated with the source as to obtain maximum transmission of energy along the guide. The optimum distance will be found to be approximately a quarter of a wave-length or an odd multiple thereof. The source 3 may be considered as simply a sine wave source but it is representative also of any source of intelligence-bearing high frequency waves, such as a carrier wave modulated with telephone, telegraph, or television signals, or the like. Similarly, at the receiving end of the system, the detector 5 connected in the same manner as the source 3 is representative of any receiving device appropriate for signals of the character generated by the source 3. Preferably, the high frequency waves are transmitted in the frequency range lying between the absolute cut-off frequency and the next higher cut-off frequency to obviate interference from spurious wave types.

Fig. 2 is quite similar to Fig. 1 except that the metallic guide is shown as a metallic pipe 11 of rectangular cross-section closed at the end by a metallic cover and provided with a metallic baffle 22 extending inwardly along the mid-line of the upper surface and parallel to the lateral surfaces. Where the physical dimensions of the source 3 make it inconvenient to dispose it in the position indicated in Fig. 1, it may be moved toward the end of the guide as shown in Fig. 2 and connected by parallel leads to the transversely disposed conductors connecting the baffle and the lower surface of the pipe.

Fig. 3 is a cross-section of Fig. 1 and it shows the distribution of the transverse electric field comprising the wave. The designation of this wave as a

$$TE_{\frac{1}{2},1}$$

wave is consistent with the scheme of designation employed in my copending application, supra.

Fig. 4 shows another type of transverse electric wave that can be sustained in the guide of Fig. 1. In its configuration it is quite similar to the $TE_{1,1}$ wave, or as it is sometimes known, the $H_{1,1}$ wave, in an unbaffled tubular metallic guide. The source or receiver may be connected between the axial edge of the baffle and a point on the pipe such that the connecting leads are aligned with the electric field, or it may be disposed below the baffle, as illustrated, with connecting leads aligned with the electric field and terminating at the pipe. Aside from its other advantages, the baffle is useful in this case in suppressing any tendency for the field to rotate out of alignment with the conductors of the receiving terminal.

Fig. 5 shows still another transverse electric wave, designated as the

$$TE_{\frac{3}{2},1}$$

and a roughly Y-shaped terminal structure conforming with the electric field and adapted to generate or receive this type of wave.

Transverse magnetic waves of four different types are shown in Figs. 6 to 9 as they would appear in the guide of Fig. 1. The dotted lines represent the lines of magnetomotive force, which lie in transverse planes.

Figs. 10 and 11 show terminal structures adapted to generate or receive transverse magnetic waves of the types illustrated in Figs. 6 and 9, respectively. The structure shown in Fig. 10 comprises two coplanar metalic plates 6 and 7, configured and disposed over the end of the metallic tube so as to leave an elongated gap between them that follows or conforms with the lines of magnetomotive force in the wave. The translating device 3 is electrically connected to the plates 6 and 7 so as, in the case of a generator, to establish an alternating difference of potential across the gap.

In the terminal structure shown in Fig. 11 there are provided two approximately elliptical coplanar electrodes 8 configured and positioned to conform roughly with the magnetic lines depicted in Fig. 9, and the translating device 3 connected in operative relation therewith.

In connection with each of the terminal structures herein disclosed, any suitable means may be employed for purifying the wave generated, that is, for suppressing spurious wave types that may be produced incidentally to the production of the desired wave type. It is contemplated too that the relatively inefficient terminal arrangements of Figs. 10 and 11 can be improved upon to effect a more efficient transfer of wave energy between the guide and the source or receiver.

Whereas the radial baffle has in each case been described as extending from the periphery of the guide to its center it will be understood that this has been for specific illustrative purposes only and that the baffle may extend a greater or lesser distance as may be desired. The greater the radial width of the baffle, the looser is the coupling between the two portions of the guide. It will be obvious that the baffle, as the term is used here and in the appended claims, loses its character as such in the limit where it extends completely across the guide, or where otherwise it serves only to subdivide the guide into a plurality of completely metallically enclosed, electrically independent passages. Where such independent passages obtain the interior of the guide is multiply connected, whereas the interior is simply connected if the baffle is radial or if otherwise it is such that at substantially every cross-section along the guide there is a (lateral) dielectric connection between all parts of the interior. From the foregoing description of the nature of the invention and from the various examples illustrated it is evident that the baffle may be defined generally as comprising one or more essentially two-dimensional conducting strips disposed longitudinally within the guide.

Although the embodiments of the invention hereinbefore described all utilize a single radial, or generaly transversely disposed planar baffle, it will be evident from the stated principles underlying these embodiments that the invention may be embodied in a wide variety of other forms. Two illustrative modifications are shown in Figs. 12 and 13.

Fig. 12 shows a guide comprising an outer cylindrical metallic pipe enclosing three tubular metallic partitions each having a longitudinal opening therein so that at all points along the guide the several semi-annular spaces are dielectrically connected. A radial metallic baffle 2 is provided extending from the periphery of the pipe to the innermost partition. The translating device 3 is connected by diametral leads from the innermost partition to a point on the outer pipe that is opposite the radial baffle. The several partitions and the radial baffle are effective in removing constraints, for transverse electric waves, and in permitting operation at lower frequencies. The guide shown in Fig. 13 is provided with a plurality of baffles lying in radial planes which also are effective in removing constraints.

What is claimed is:

1. A transmission system including a wave guide comprising a metallic pipe, means for establishing in said pipe electromagnetic waves of a character such that the guide presents to them the characteristics of a high-pass filter, and means for depressing the absolute cut-off frequency of said guide comprising a metallic baffle extending longitudinally within said pipe and dividing the interior of said pipe into only simply connected portions, said baffle being maintained in substantially the same relative position throughout the length of said pipe whereby said waves are unchanged in type.

2. A wave guide comprising a metallic pipe having a longitudinal conducting baffle therein extending inwardly from the periphery and having only one lateral connection with said periphery whereby the interior of said pipe is a simply connected space, and means for generating electromagnetic waves in said guide at a frequency above the cut-off frequency, said baffle being substantially coextensive with said pipe and the cross-sectional configuration of said pipe and baffle being substantially the same throughout their length.

3. In a signal transmission system, a wave guide comprising a tubular metallic pipe and a planar longitudinal baffle coextensive with said

pipe and lying in a diametral plane therein, said baffle extending laterally in one direction only to the periphery of said pipe whereby the space within said pipe is simply connected, and means for transmitting through said guide signal-modulated electromagnetic waves at frequencies above the cut-off frequency of said guide.

4. In a system for the transmission of guided electromagnetic waves of a character such that transmission occurs only at frequencies above a critical frequency dependent on the type of wave, a wave guide comprising a metallic pipe, at least one metallic baffle longitudinally disposed within said pipe, and means for generating electromagnetic waves for transmission through said pipe, said waves being of such type that the critical frequency therefor is the absolute cut-off frequency of said guide and said waves occupying a frequency range lying between said cut-off frequency and the next higher critical frequency, the cross-sectional configuration of said pipe and baffle being substantially the same throughout the length of said guide whereby said waves undergo no change in type, and said baffle being so configured and arranged as to leave a substantially continuous lateral dielectric connection between all parts of the interior of said pipe.

5. A wave guide comprising a metallic pipe containing a gaseous dielectric medium and at least one planar metallic baffle longitudinally disposed within said pipe and dividing the interior of said pipe throughout its length into a plurality of symmetrical, laterally partially bounded compartments, and means for establishing electromagnetic waves in said guide for transmission therethrough, said guide presenting to said waves the characteristics of a high-pass filter.

6. A high frequency transmission system including a wave guide comprising a metallic pipe containing a gaseous dielectric medium and a flat metallic strip disposed longitudinally within said pipe and coextensive therewith, said strip extending inwardly from the periphery of said pipe and separating the interior of said pipe into two symmetrical, laterally dielectrically connected portions, and means for generating within said guide, for transmission therethrough, electromagnetic waves of such characteristic field pattern that they are propagated only at frequencies exceeding a critical frequency dependent on the transverse dimensions of said pipe.

7. A combination in accordance with claim 6 in which said generating means comprises a transversely disposed conductor electrically connected between the innermost edge of said strip and a point on said pipe in alignment with said strip, and means interposed in said conductor for applying an alternating difference of potential thereto.

8. A combination in accordance with claim 6 comprising a translating device within said pipe and electrical connections thereto extending along lines of electric force of said waves substantially perpendicular to the plane of said strip.

9. A guide for the transmission of electromagnetic waves of ultra-high frequency comprising a metallic pipe and a roughly C-shaped channel concentrically enclosed thereby and substantially coextensive therewith for reducing the absolute transmission cut-off frequency of said guide, said guide having substantially the same cross-sectional configuration throughout its length.

10. A guide in accordance with claim 9 having in addition a longitudinal planar baffle extending between the walls of said pipe and channel.

11. A uni-conductor guide for ultra-high frequency electromagnetic waves comprising a tubular metallic pipe having several symmetrically disposed longitudinal baffles, said baffles at every point along said guide extending inwardly and radially from the periphery of said pipe but not to the axis thereof.

12. A wave guide consisting of a metallic pipe having a longitudinal inwardly extending metallic baffle or semi-partition such that the space within said pipe is simply connected and means for applying high frequency electromagnetic waves to said guide for transmission through the interior thereof, said waves being of such character that said guide presents to them a high-pass transmission characteristic and said baffle or semi-partition being so constructed and arranged as to preserve unaltered the characteristic field pattern of said waves.

13. A wave guide comprising a metallic pipe and means for transmitting therethrough electromagnetic waves of a nature such that the guide presents to them the characteristics of a high-pass filter, the interior of said pipe being metallically divided throughout its length into two or more portions that are continuously and loosely coupled together through a lateral dielectric connection between them, the interior of said pipe being of substantially the same cross-sectional configuration throughout its length whereby the said waves are unchanged in type in their passage therethrough.

14. An electric signaling system including a wave guiding structure comprising a tubular metallic pipe, means for launching in said pipe for transmission therethrough electromagnetic waves of a character such that the guide presents the characteristics of a high-pass filter, means for receiving said waves after transmission through said pipe, said receiving means being most effective when disposed in a particular angular relation with reference to the angular orientation of said waves, and means for insuring that said particular angular relation obtains comprising means for fixing the angular orientation of said waves throughout the length of said guide.

15. A combination in accordance with claim 14 in which the last-mentioned means comprises a metallic rib on the inner surface of said pipe.

16. A system for the long distance transmission of transverse electric waves comprising a metallic pipe extending between geographically separated places, said pipe enclosing a simply connected dielectric medium, and metallic means disposed longitudinally within said pipe and substantially coextensive therewith adapted to release a constraint on said transverse electric waves, whereby at least one of the critical frequencies for said waves is lowered.

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