

Feb. 1, 1938.

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2,106,725

DIELECTRIC GUIDE SYSTEM

Filed April 11, 1936

FIG. 1

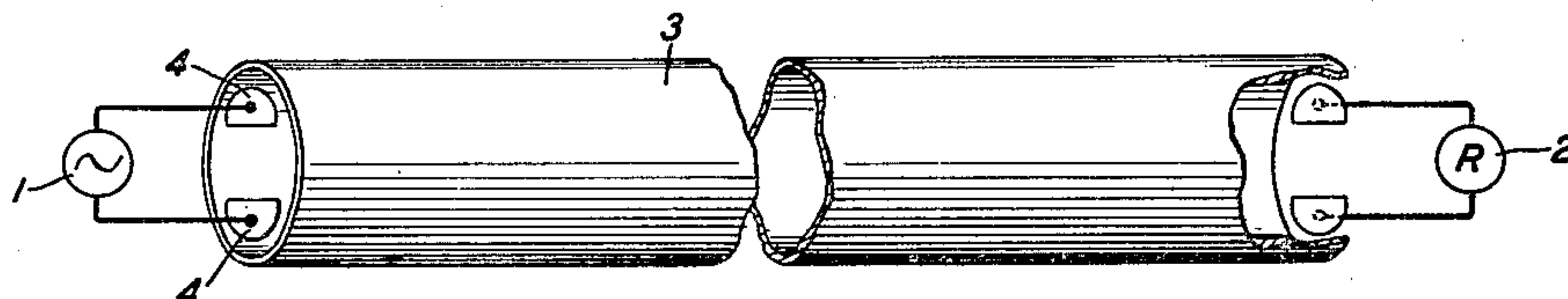


FIG. 2

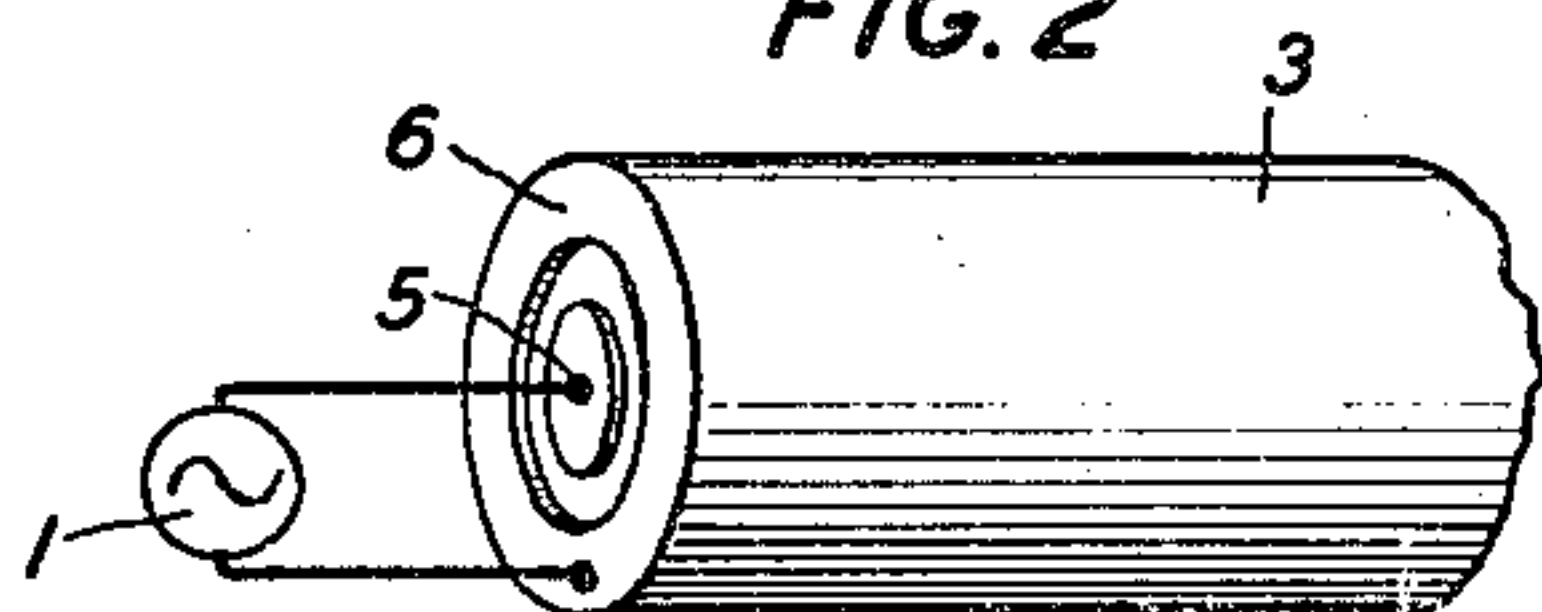


FIG. 3

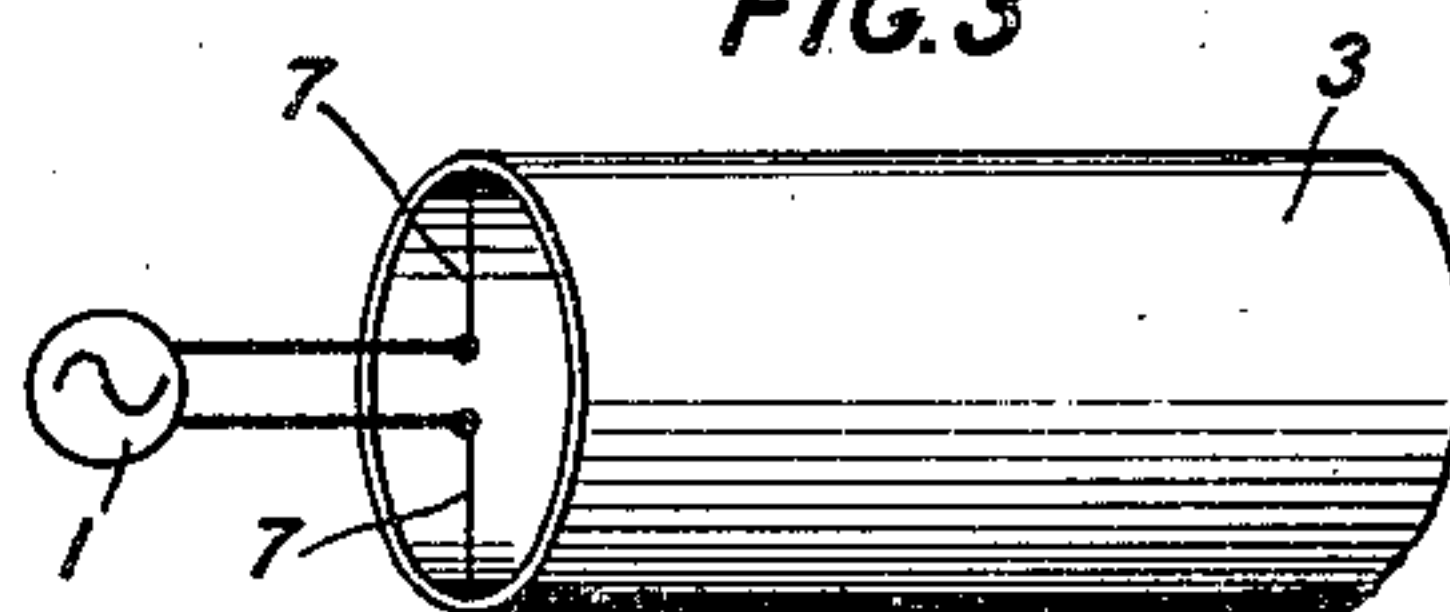


FIG. 4

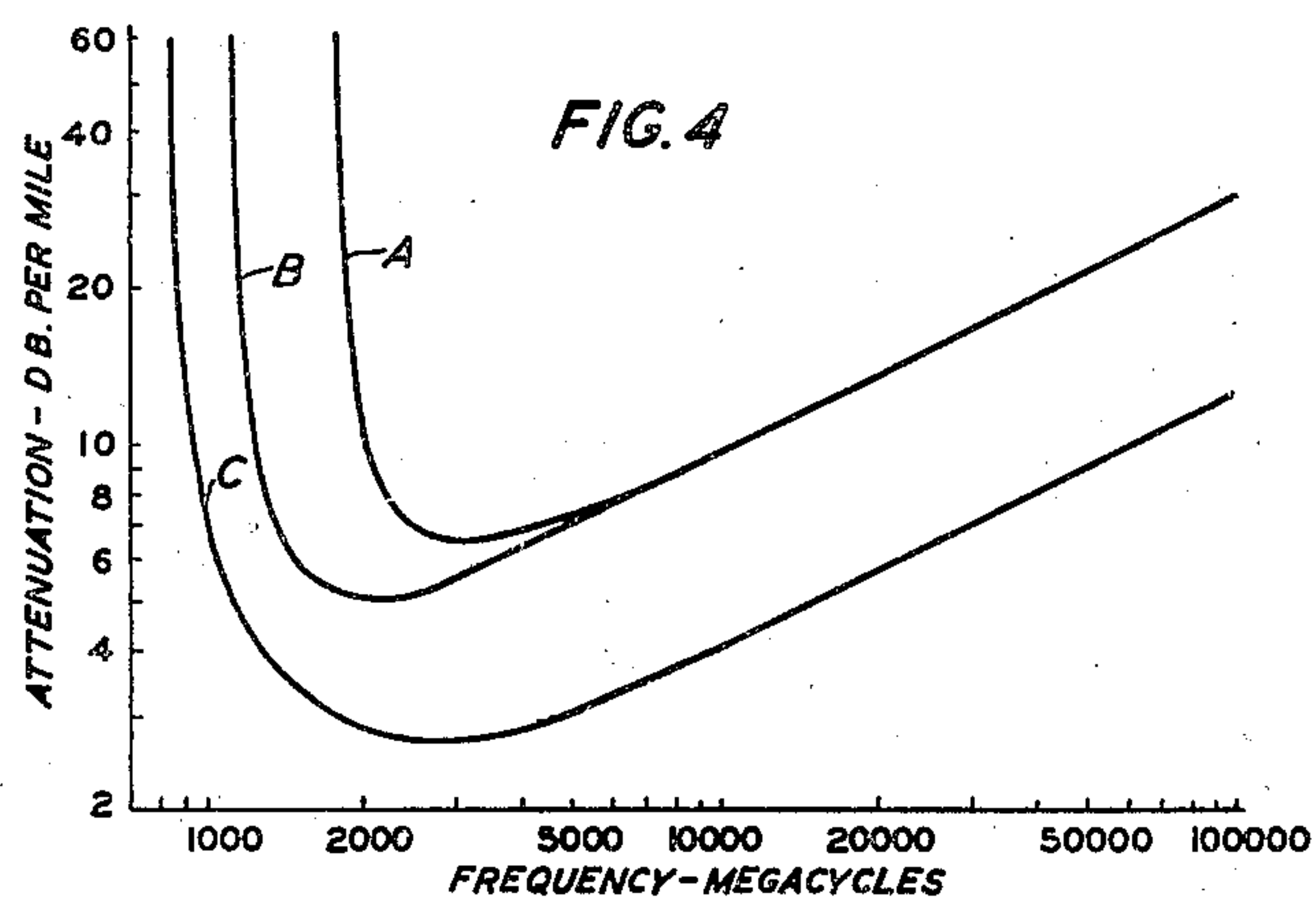
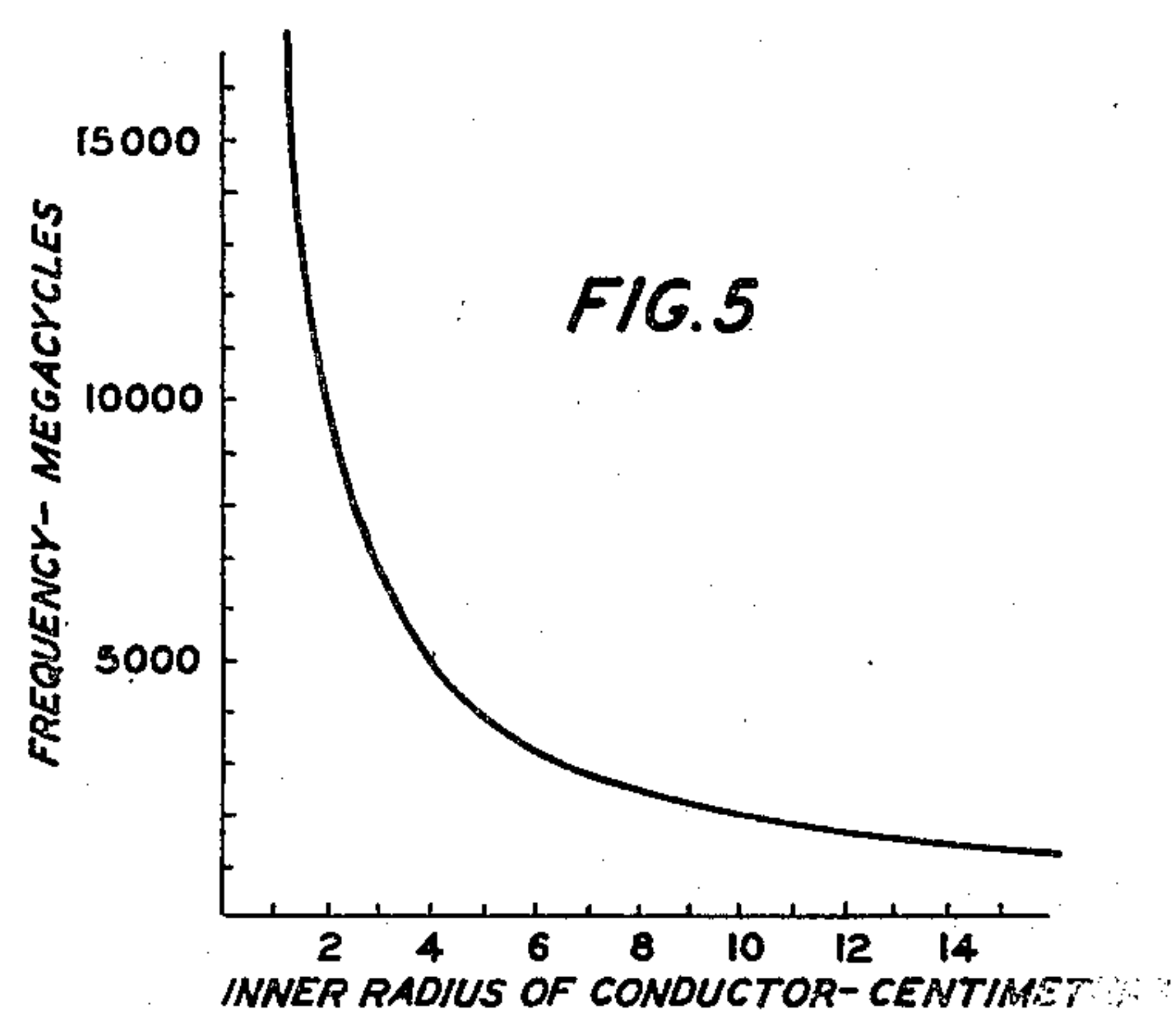


FIG. 5



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2,106,725

DIELECTRIC GUIDE SYSTEM

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Application April 11, 1936, Serial No. 73,955

8 Claims. (Cl. 178—44)

This invention relates to systems for the transmission of electromagnetic waves of ultra-high frequencies and more particularly to systems for the transmission of such waves over dielectric guides.

It has been shown heretofore how electromagnetic waves of sufficiently high frequency may be transmitted through rods of dielectric material, metal-sheathed or otherwise, hollow conducting structures such as metallic pipes, and other equivalent structures characterized by a lateral boundary comprising an electromagnetic discontinuity.

The principal object of the present invention is to reduce the attenuation of the waves transmitted through a dielectric guide, or in another aspect to reduce the effective resistance of the guide to dielectrically guided waves. A more specific object of the invention is to secure an optimum correlation between the frequency or frequencies of the guided waves and the transverse dimensions or other properties of the guiding structure.

The present invention is based on applicant's discovery of the laws governing the variation of the attenuation of dielectrically guided waves with frequency and the fact that at a certain frequency the attenuation of each of several different types of such waves is minimum. In accordance with the present invention, the frequency or frequencies chosen for the operation of a dielectric guide system is, or are, such that the attenuation is minimum, or if the operating frequency be predetermined, the dimensions and physical properties of the guiding structure are so related to that frequency as to result in minimum attenuation.

The nature of the present invention, together with other objects, features and advantages thereof, will appear more fully in the following discussion and detailed description of several specific embodiments of the invention, reference being made to the accompanying drawing, in which:

Figure 1 illustrates a typical dielectric guide system;

Figs. 2 and 3 show alternative terminal electrode structures;

Fig. 4 shows graphically the relation between attenuation and frequency for typical systems in accordance with Figs. 1, 2 and 3; and

Fig. 5 shows graphically the relation between the optimum frequency and the dimensions of the guide for one specific type of wave.

Of the waves transmissible along a dielectric guide two general types have been identified: transverse magnetic and transverse electric. These two general types have been defined and illustrated in an application for Letters Patent, Serial No. 56,959, filed by S. A. Schelkunoff, on December 31, 1935. Transverse magnetic waves, the first to be dealt with here, are characterized by the fact that the vector representing the magnetic component of the wave lies substantially wholly in a plane orthogonal to the direction of propagation, whereas the vector representing the electric component does not. Transverse electric waves are characterized in a similar manner by the fact that the vector representing the electric component of the wave lies substantially wholly in a plane orthogonal to the direction of propagation, whereas the magnetic component does not.

In Fig. 1 is represented a typical dielectric guide system adapted for the long distance transmission of transverse electric waves from a generator or source 1 to a receiver 2. The guide illustrated comprises a hollow metallic structure 3, a copper tube, for example, evacuated or filled with a fluid or solid dielectric material, which may conveniently be air. The source 1 is a generator of high frequency waves, and these waves may be modulated with speech, telegraph, television or other signals to produce a wide band of waves for application to the metallic terminal electrode structure 4 of the guide 3. At the receiving end of the system a similar electrode structure may be employed to convert the dielectrically guided waves into conduction currents suitable for operation of the detector or receiver 2.

Where the dielectric guide is a metallic tube, the attenuation of any transverse magnetic wave in it is given by Equation 4 of the Schelkunoff application, *supra*:

$$\alpha = \frac{R_p}{\eta a} \left(1 - f_c^2/f^2 \right)^{-1/2} \text{ nepers/cm.}, \quad (1)$$

where R_p is the intrinsic resistance of the metal comprising the tube, the intrinsic resistance being the real part of its intrinsic impedance;

$$R_p = \sqrt{\frac{\pi \mu_p f}{g_p}} \text{ ohms}; \quad (2)$$

$$\eta = \sqrt{\frac{\mu}{\epsilon}} \text{ ohms}; \quad (3)$$

and the other symbols employed have the following significance:

- a = inner radius of the tube in cms.
 f_c = cut-off frequency
 f = applied frequency
 μ = intrinsic inductance of the dielectric in henries/cm.
 ϵ = intrinsic capacity of the dielectric in farads/cm.
 μ_p = intrinsic inductance of the metal in henries/cm.
 g_p = intrinsic conductance of the metal in mhos/cm.

In empty space, μ is $4\pi 10^{-9}$ henries/cm. and ϵ is $10^{-11}/36\pi$ farads/cm. For copper, μ_p is $4\pi 10^{-9}$ henries/cm., and g_p is 5.800×10^5 mhos/cm. The cut-off frequency f_c to which reference has been made, is the critical frequency above which dielectrically guided waves of a given type are freely propagated along any particular dielectric guide and below which the attenuation is practically infinite.

For a metallic tubular guide of predetermined size and material, Equation 1 may be rewritten in the form:

$$\alpha = K\sqrt{f}(1 - f_c^2/f^2)^{-1/2}, \quad (4)$$

where K is a constant.

To determine the frequency at which the attenuation is minimum,

$$\frac{\partial \alpha}{\partial f}$$

is equated to zero. Carrying out this operation and solving for the optimum frequency f_m ,

$$f_m = \sqrt{3}f_c \text{ cycles/sec.} \quad (5)$$

Equation 5 relates the optimum frequency with the cut-off frequency f_c . The latter is determinable, in turn, from the relation

$$f_c = \frac{kv}{2\pi a} \text{ cycles/sec.,} \quad (6)$$

where v is the velocity of light in free space in centimeters per second and k is the modular constant appropriate to the mode and order of the particular dielectrically guided wave that is to be employed. A schedule of the modular constants for transverse magnetic waves follows:

Transverse magnetic waves in circular tubes

Order n	Mode m			
	1	2	3	4
0	2.40	5.52	8.65	11.79
1	3.83	7.02	10.17	13.32
2	5.14	8.42	11.62	14.80
3	6.38	9.76	13.02	16.22

Equations 5 and 6 combine to yield the following expression for the optimum relation between the operating frequency f_m and the internal radius a of the tubular guide:

$$f_m = \frac{\sqrt{3}kv}{2\pi a} \text{ cycles/sec.} \quad (7)$$

With the system illustrated in Fig. 1, a transverse magnetic wave of first order traveling in the first mode may be generated. Curve A of Fig. 4 shows how the attenuation of this wave varies with frequency in a tubular copper guide of eight-inch internal diameter. The optimum frequency, it will be found by solution of Equation 7 is 3120 magacycles per second.

Fig. 2 shows a terminal structure comprising an axial metallic disk 5 and a concentric metallic annular electrode 6 suitable for the generation and reception of transverse magnetic waves of zero order and first mode. This wave is of particular interest because it has a low cut-off frequency, the lowest, in fact of all transverse magnetic waves. For this type of wave, Equation 7 reduces to:

$$f_m = \frac{1.99 \times 10^{10}}{a} \text{ cycles/sec.} \quad (8)$$

Equation 8 is shown in graphical form in Fig. 5. Curve B of Fig. 4 shows the relation between frequency and the attenuation of this type of wave in a copper tube of eight-inch internal diameter.

For specific example, suppose it be desired to determine the optimum frequency at which to transmit waves of the character last described in a metallic tube of four-inch inner radius. From Equation 8 or from Fig. 5, it may readily be found that the optimum frequency is approximately 1960 megacycles per second. If the waves occupy a wide frequency band, the band should be roughly centered about the optimum frequency.

It has been tacitly assumed that the dielectric enclosed by the metallic tube is substantially gaseous. If it is not substantially gaseous, the effect is twofold. First, the cut-off frequency f_c is decreased in the ratio of the square root of the dielectric constant of the dielectric material referred to air as unity. Second, the attenuation is increased by losses in the dielectric material, these losses being in general a complex function of frequency. In such cases it is necessary to determine the dielectric loss experimentally, combine it with the computed attenuation and then solve graphically for the optimum frequency.

Transverse electric waves remain to be considered. Fig. 3 shows a terminal structure comprising two radial conductors 7, suitable for the generation of one type of such waves. This same structure is adapted also for the receiving end of a dielectric guide system in the manner illustrated in Fig. 1. Transverse electric waves of first order and first mode may be generated with the structure shown in Fig. 3, and curve C of Fig. 4 shows how the attenuation of this type of wave varies with frequency in a copper tube of eight-inch internal diameter.

The attenuation of transverse electric waves of order n may be conveniently expressed in substantially the same form as Equation (4.1) of Schelkunoff, *supra*.

$$\alpha = \frac{R_p}{\eta a} \left(\frac{n^2}{k^2 - n^2} + f_c^2/f^2 \right) (1 - f_c^2/f^2)^{-1/2} \text{ nepers/cm.,} \quad (9)$$

where k is the modular constant appropriate to the order and mode of the wave. A schedule of the modular constants for transverse electric waves follows:

Transverse electric waves in circular tubes

Order n	Mode m		
	1	2	3
0	3.83	7.02	10.17
1	1.841	5.332	8.536
2	3.054	6.705	9.965
3	4.201	8.015	11.344

To determine the optimum operating frequency,

$$\frac{\partial \alpha}{\partial f}$$

is equated to zero, whereupon it is found that the following equation must be satisfied:

$$\frac{f_c^4}{f^4} - 3\left(\frac{n^2}{k^2 - n^2} + 1\right)\frac{f_c^2}{f^2} + \frac{n^2}{k^2 - n^2} = 0 \quad (10)$$

Equation 10 is a quadratic in $(f_c/f)^2$, which can readily be solved, for any particular values of k and n , to yield the exact optimum frequency.

An approximate solution of Equation 10 that is accurate to within three per cent. and therefore accurate enough for all practical purposes, is as follows:

$$f_m = \sqrt{3} \frac{k}{n} f_c, \quad (11)$$

or, substituting from Equation 6,

$$f_m = \frac{\sqrt{3} k^2 v}{2\pi n a}, \quad (12)$$

where all factors on the right-hand side of the equation are known as soon as the inner radius of the tubular guide and the type of wave have been fixed upon.

As a typical example, assume that a metallic tube with air dielectric is to be used for the transmission of transverse electric waves of the first mode and first order, and that the tube has an inner radius of four inches. The value of k for this particular wave is found from the schedule of modular constants to be 1.84. The cut-off frequency is found from Equation 6 to be 865 megacycles per second. The frequency at which attenuation is minimum is then found from Equation 11 to be approximately 2750 megacycles per second.

The principles of this invention can be extended to the determination of the optimum frequency for transmission in hollow conductors of non-circular cross-section since it is evident that waves of transverse electric and magnetic types can be sustained therein. Thus the guide may be rectangular, elliptical or otherwise in cross-section. The cut-off frequencies are given by modular constants which are obtained by applying boundary conditions to the mathematical equations which express the field as in Schelkunoff, *supra*. Thus there will be a series of cut-off frequencies, each series being a function of the cross-sectional shape of the guide. The attenuation formulas also are dependent on the cross-section of the conductor but the frequency for which the attenuation of a particular wave traveling along a tube of particular cross-section is a minimum can be obtained as has been done above for the tubes of circular cross-section by a process of mathematical minimization. The frequency for minimum attenuation will be found in each case to be a function of the cut-off frequency.

What is claimed is:

1. A hollow metallic guide and means for es-

tablishing therein dielectrically guided waves, the frequency of said waves being so related to the transverse dimensions of said guide that attenuation is substantially minimum.

2. A combination in accordance with claim 1 in which said waves are transverse magnetic and the frequency is $\sqrt{3}f_c$ where f_c is the cut-off frequency of said guide.

3. A combination in accordance with claim 1 in which said waves are transverse electric and the frequency is $\sqrt{3}kf_c/n$ in accordance with Equation 11.

4. A wave guide comprising a dielectric medium and metallic means defining the lateral boundary thereof, and means for establishing within said guide electromagnetic waves of a character such that there is a transmission cut-off frequency dependent on the transverse dimensions of said guide and the index of refraction of said medium, the frequency of said waves being higher than said cut-off frequency and so related thereto that the attenuation of said waves is substantially minimum.

5. A wave guide consisting essentially of a metallic pipe enclosing a dielectric medium, and means for establishing progressive electromagnetic waves in said dielectric medium, the attenuation of said waves being a function of frequency and the frequency of said waves being such that the attenuation is substantially minimum.

6. In a high frequency transmission system, a wave guide comprising a metallic pipe, and means for transmitting through the interior of said pipe electromagnetic waves of a character such that there is a critical frequency separating the propagation range from a lower frequency range of zero or negligible transmission, the frequency of said waves being approximately that for which the attenuation is minimum.

7. In combination, a wave guide comprising a metallic pipe, and means for establishing in said pipe intelligence-bearing electromagnetic waves of the transverse magnetic type, for which there is a cut-off frequency functionally related to the transverse dimensions of said pipe, said waves occupying a wide frequency band including a frequency that is of the order of $\sqrt{3}$ times the said cut-off frequency, whereby said waves are transmitted with low attenuation.

8. A transmission system including as a wave guide a metallic pipe carrying within it high frequency electromagnetic waves of the transverse electric type such that said guide exhibits a high-pass filter characteristic, the frequency of said waves and the transverse dimensions of said pipe being so related that the attenuation is substantially minimum.

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