

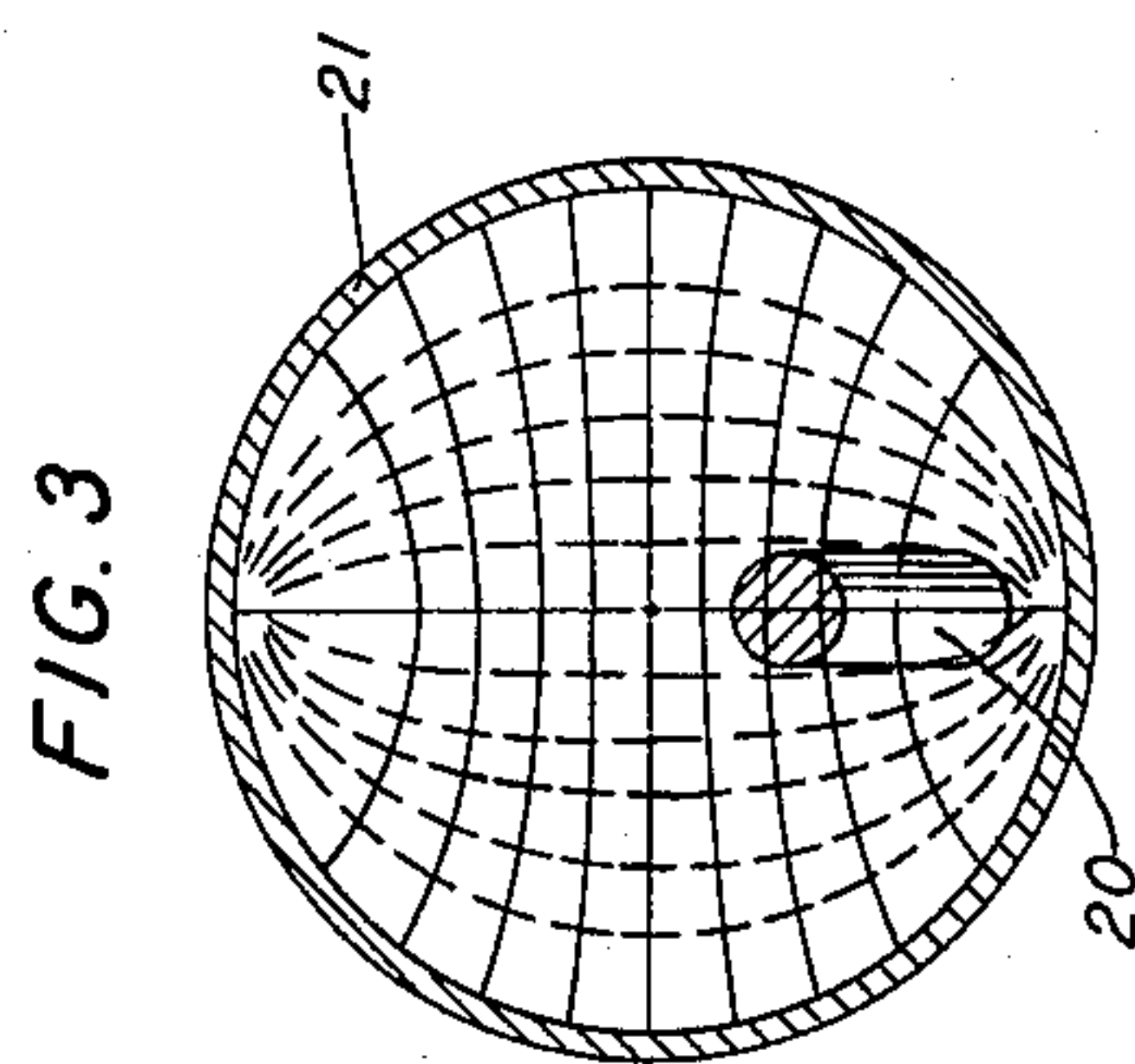
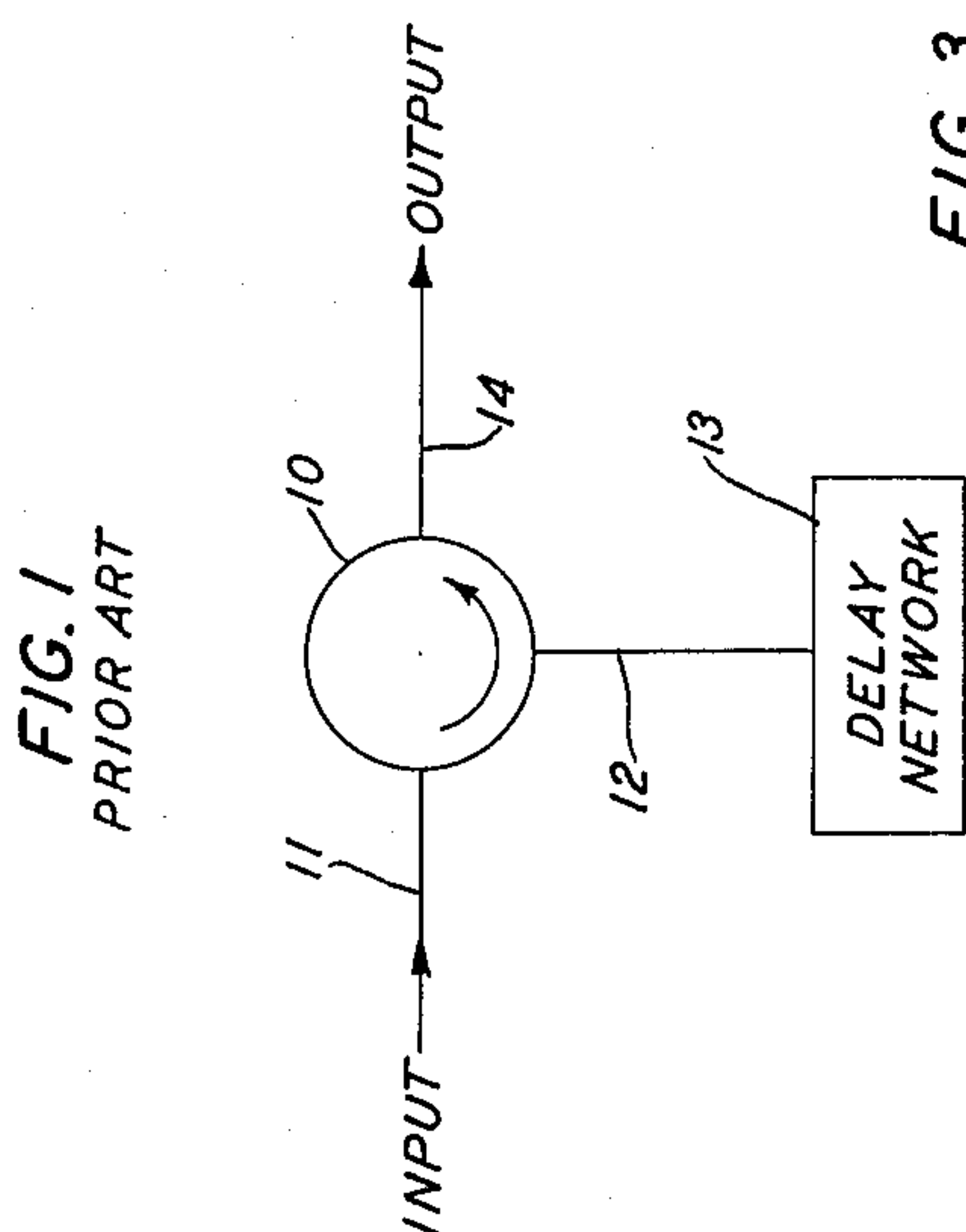
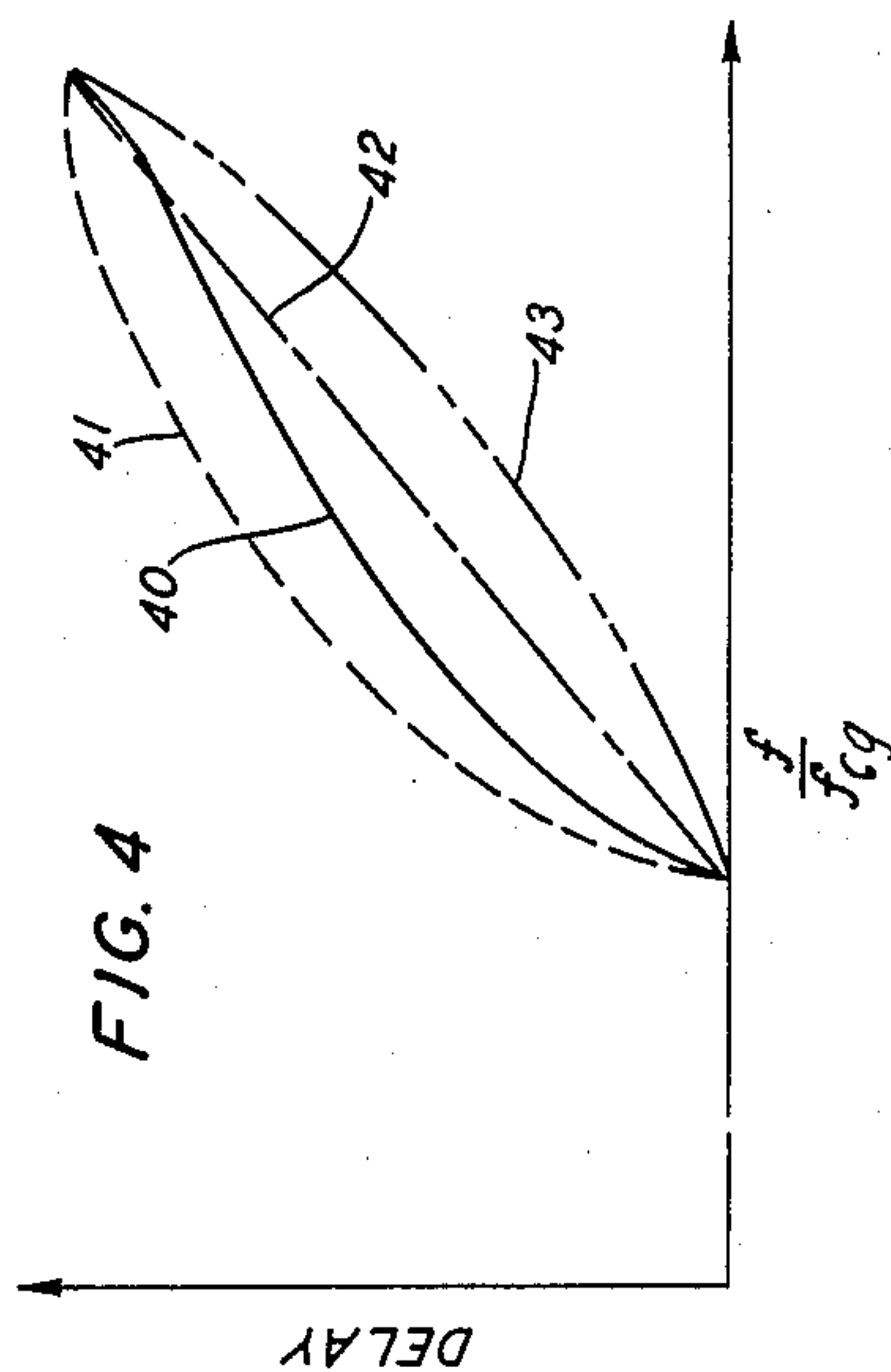
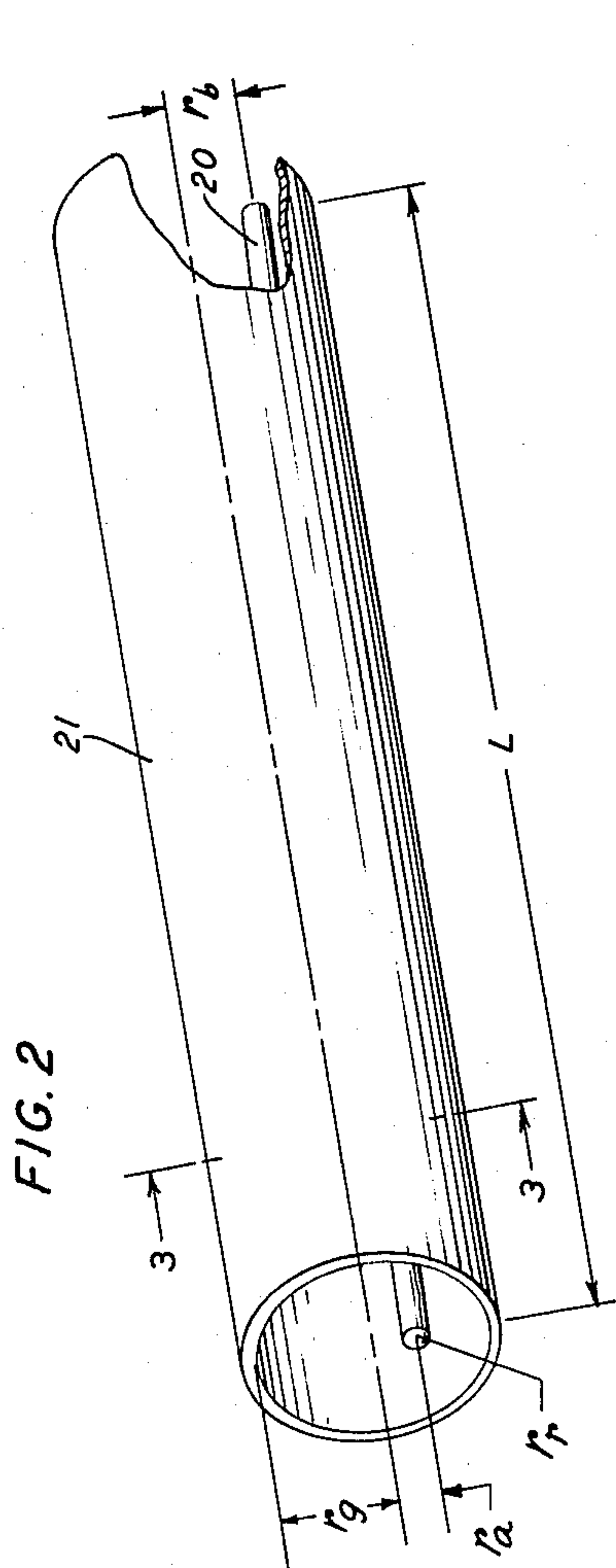
May 24, 1966

KENNETH W. WOO
NOW BY CHANGE OF NAME KENNETH E. WOO
MICROWAVE DELAY EQUALIZER

3,253,238

Filed Nov. 12, 1963

3 Sheets-Sheet 1



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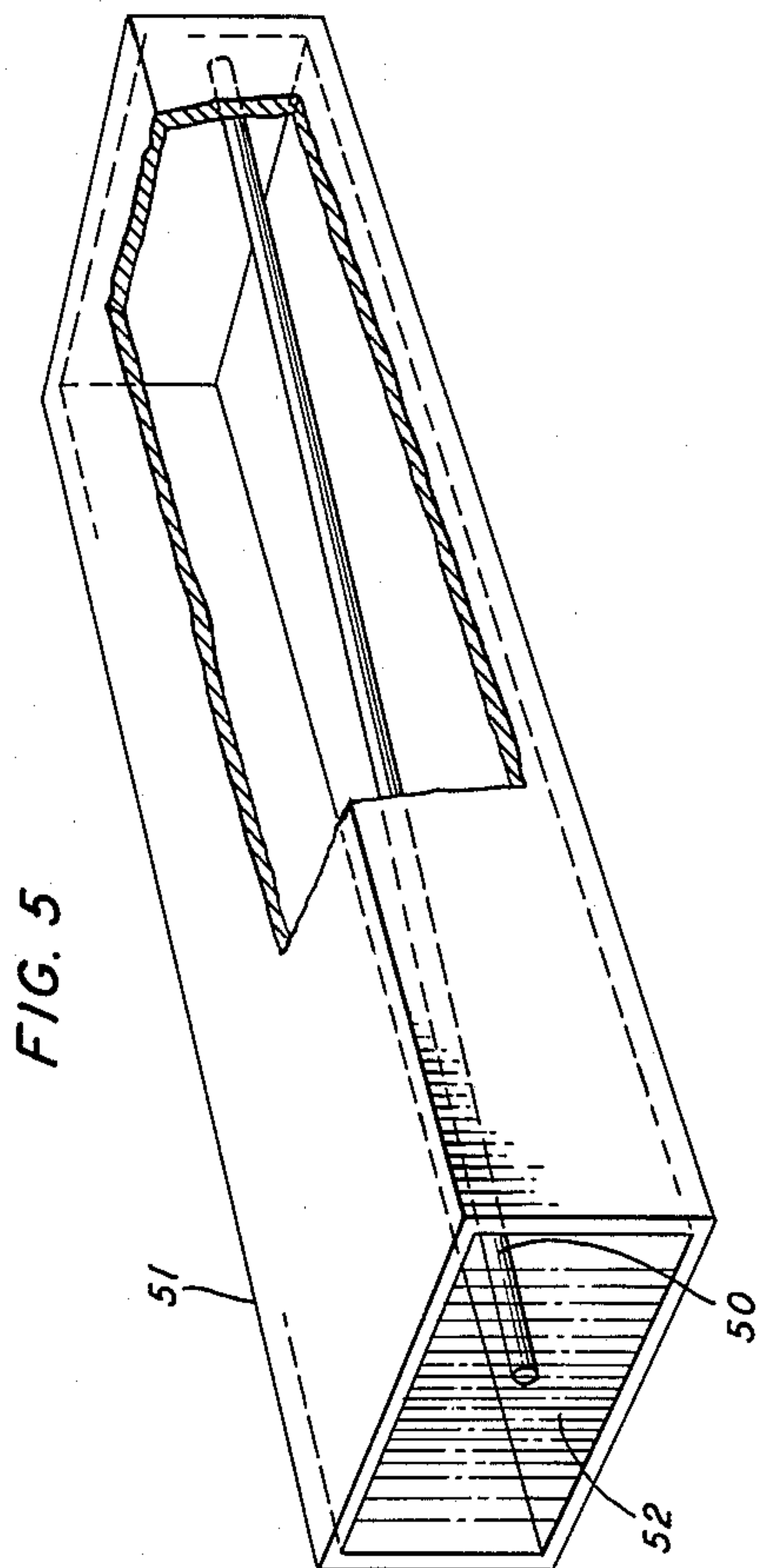
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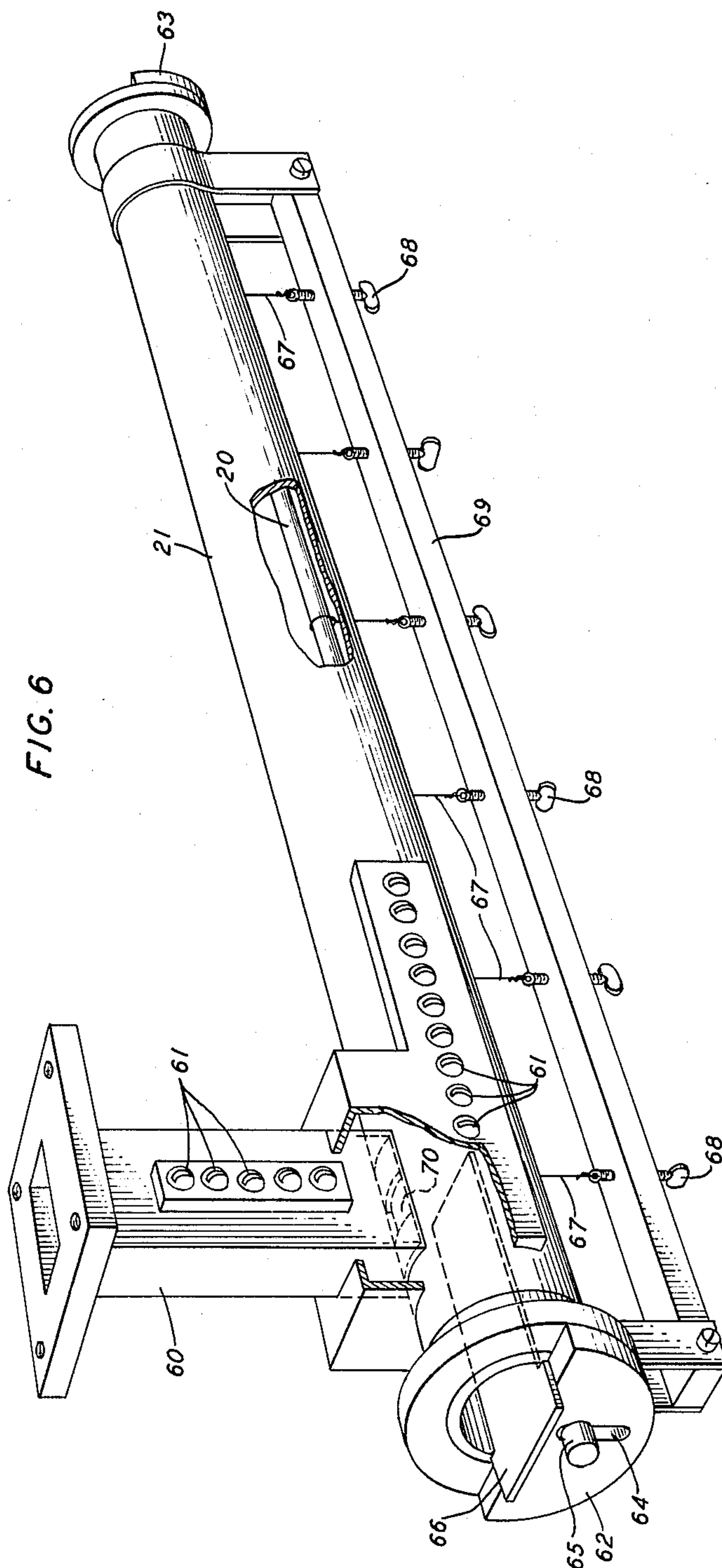
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3,253,238

MICROWAVE DELAY EQUALIZER

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This invention relates to broadband electromagnetic wave transmission systems and more specifically to delay equalizers for use in such systems.

It is well known that in high frequency transmission systems, waves of different frequencies do not propagate at the same velocity. For example, in the transmission of a broadband microwave signal through a waveguide, the higher frequencies travel at a higher group velocity than the lower frequencies. If uncorrected, this difference in group propagation velocity gives rise to appreciable and, in some cases, serious distortion of the signal. The resulting distortion, termed "delay distortion," can be corrected by suitably delaying the faster propagating frequency components with respect to the slower propagating frequency components. The difficulty, however, is in obtaining a corrective network which is both simple in structure and which adequately compensates over the frequency range of interest.

Accordingly, a general object of the present invention is to reduce delay distortion in microwave systems.

Delay equalizers for performing this function at lower frequencies can be constructed of lumped parameter elements such as capacitors and inductors. At higher frequencies, however, it is desirable, and in most cases necessary, to utilize distributed parameter networks. One such device is described in U.S. Patent No. 2,863,126 granted to J. R. Pierce on December 2, 1958. Delay equalizers of the type described by Pierce, however, have certain inherent disadvantages which make them undesirable for some applications. First, devices of this type utilize sections of tapered waveguide fabricated with extremely close dimensional tolerances. Secondly, since the delay characteristics of such devices are determined by the physical dimensions of the tapered guide, they are difficult to adjust. Even when adjustments of such devices can be made, they are generally in the nature of minor trimming or padding adjustments and do not significantly affect the delay characteristics.

It is therefore another object of the present invention to provide a microwave delay equalizer having an easily adjustable characteristic over a wide range.

In accordance with the principles of the present invention, the above objects are accomplished by providing a perturbation along the interior of an otherwise uniform microwave waveguiding structure. The perturbation, in effect, alters the electrical cross-sectional dimensions of the waveguide. By adjusting the position of the perturbing member, the apparent electrical cross-section of the waveguide can be made to "taper" in any desired manner.

As in the case of the prior art tapered waveguide delay equalizers, the present invention accomplishes delay equalization by means of cutoff reflection. When a broadband microwave signal is applied to the perturbed waveguide section, each frequency component thereof is reflected at a different point along the waveguide length. In general, the lower frequency components are reflected near the guide entrance, whereas the higher frequency components propagate farther into the guide before being reflected. Because of this greater distance of propagation, the reflected higher frequency components have a longer round trip transmission path and a corresponding increased delay time.

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Since the input signal to the delay equalizer is ordinarily characterized by frequency components which are delayed more for the lower than for the higher frequency components, phase delay compensation or equalization is obtained.

The above-mentioned and other features and objects of this invention will become more apparent by reference to the following description taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a generalized block diagram of a delay equalizer;

FIG. 2 is a pictorial view, partially broken away, of a simplified embodiment of the present invention;

FIG. 3 is a cross-sectional view of the embodiment of FIG. 2 showing the electric field orientation therein;

FIG. 4 is a graphical representation of the time delay versus frequency characteristics of the present invention;

FIG. 5 is a simplified pictorial view, partially broken away, of another embodiment of the present invention; and

FIG. 6 is a pictorial view, partially broken away, of a more complete version of the embodiment of FIG. 2.

Referring more specifically to the drawings, FIG. 1 is a block diagram of a generalized delay equalizer circuit well known in the art. The incoming signal, which ordinarily contains components extending over a broad band of frequencies, is applied to input port 11 of a circulator 10. This signal passes through circulator 10 out port 12 to a delay network 13. Delay network 13 selectively delays the various frequency components of the input signal and reflects them back through circulator 10 by way of port 12 to the output port 14.

Thus, if the input signal has, during transmission, experienced a delay which is inversely proportional to frequency, the preferred characteristic of delay network 13 is such that the overall delay is directly proportional to frequency. If the delay characteristic of network 13 is correctly adjusted, the output signal from the delay equalizer is substantially compensated and the distortion caused by unequal time delay minimized.

A microwave delay network, in accordance with the invention for use in such a delay equalizer circuit is shown in the simplified, partially broken away, pictorial view of FIG. 2. The illustrative embodiment of FIG. 2 comprises a conductive rod 20 of uniform radius r_r which extends within a hollow tube or circular waveguide section 21 of inner radius r_g and length L. For purposes of simplicity, the supporting means for rod 20 and the input source of the microwave signal have been omitted from FIG. 2 but have been included in FIG. 6 to be described hereinafter.

The orientation of rod 20 can be described with reference to the electric and magnetic field lines within guide 21. A cross-sectional view of the structure of FIG. 2 is shown in FIG. 3. The solid lines represent the electric field lines of the input signal when propagating in the TE_{11} wave mode whereas the dashed lines represent the magnetic field lines for this mode. Although other wave modes can be utilized, the operation of the present invention will be described herein in terms of the TE_{11} wave mode.

Rod 20 is preferably oriented so that its axis or centerline lies in a plane which includes the axis or centerline of guide 21 and is perpendicular to the electric field lines. This plane will be referred to hereinafter as the plane of symmetry. At the input end or entrance of the device, the centerline of rod 20 is a distance r_a from the centerline of guide 21, and gradually slants so that its centerline lies a distance r_b greater than r_a from the centerline of the guide at the other end thereof.

Referring to the cross-sectional view of FIG. 3, it is seen that rod 20 is oriented so as to extend from a region of substantially maximum electric field at the entrance of

guide 21 to a region of substantially maximum magnetic field at the other end of the guide. As mentioned above, it is advantageous that the centerline of rod 20 lie in the plane of symmetry. When the axis of rod 20 lies in this plane the device exhibits a minimum tendency to convert the propagating wave energy to other wave modes, principally the TEM mode.

The operation of the embodiment of FIG. 2 can be explained in terms of perturbation theory. A concise statement of this theory appears in the treatise "Microwave Electronics" by J. C. Slater, published by D. Van Nostrand Co., Inc., New York, 1950, at page 81. Briefly, this theory states that a perturbation, such as that produced by rod 20, in the interior of a waveguide alters the effective electrical dimensions of the waveguide. Whether the perturbation increases or decreases the effective electrical dimensions of the guide depends primarily upon the position of the perturbation with respect to the propagating wave energy. Generally, a perturbation at or near a region of large electric field (small magnetic field) increases the effective electrical cross section of the guide; whereas a perturbation at or near a region of small electric field (large magnetic field) decreases the effective electrical cross section of the guide. Since, in general, the cutoff frequency of the waveguide is inversely related to the cross-sectional dimensions thereof, it is apparent that by introducing such perturbations into a guide, the cutoff frequency is also changed.

Referring once again to the embodiment of FIG. 2, it is seen that rod 20 constitutes a perturbation whose location varies continuously at successive cross sections of guide 21 from a region near maximum electric field to a region near maximum magnetic field. In this manner, the effective cutoff frequency of guide 21 varies at successive cross sections from a value lower than the unperturbed cutoff frequency at the entrance to a value higher than the unperturbed cutoff frequency at the end. The theoretical expression for the delay time τ of a given input signal of frequency f for the embodiment of FIG. 2 is given approximately by:

$$\tau = \frac{4Lr_g f}{\pi c(r_b - r_a)\sqrt{f_{b1}^2 - f_{a1}^2}} \left\{ K \left[\sqrt{\frac{f^2 - f_{a1}^2}{f_{b1}^2 - f_{a1}^2}} \right] F \left[\sqrt{\frac{f^2 - f_{a1}^2}{f_{b1}^2 - f_{a1}^2}}, \sin^{-1} \frac{\sin \frac{\pi}{2} \frac{r_a}{r_g}}{\sqrt{\frac{f^2 - f_{a1}^2}{f_{b1}^2 - f_{a1}^2}}} \right] \right\} \quad (1)$$

In this equation c represents the velocity of light in free space $= 3 \times 10^8$ meters per second, F is the elliptic integral of the first kind and K is the complete elliptic integral of the first kind. In addition, f_{a1} is the cutoff frequency at the entrance of guide 21 when $r_a = 0$ and f_{b1} is the cutoff frequency at the end of guide 21 when $r_b = r_g$. These symbols f_{a1} and f_{b1} are given, in turn, by the equations:

$$f_{a1} = f_{cg} \sqrt{1 - 4.189 \left(\frac{r_g}{r_g} \right)^2} \quad (2)$$

$$f_{b1} = f_{cg} \sqrt{1 + 2.837 \left(\frac{r_g}{r_g} \right)^2} \quad (3)$$

where f_{cg} is the cutoff frequency of guide 21 in the absence of rod 20.

The bandwidth of the embodiment of FIG. 2 is equal to the difference between the cutoff frequency at the end of guide 21, f_b , and the cutoff frequency at the entrance of the guide, f_a . These frequencies are given by the expressions:

$$f_b = \left[(f_{b1}^2 - f_{a1}^2) \sin^2 \frac{\pi r_b}{2r_g} + f_{a1}^2 \right]^{1/2} \quad (4)$$

$$f_a = \left[(f_{b1}^2 - f_{a1}^2) \sin^2 \frac{\pi r_a}{2r_g} + f_{a1}^2 \right]^{1/2} \quad (5)$$

FIG. 4 is a graphical representation of the time delay of the embodiment of FIG. 2 as a function of normalized frequency f/f_{cg} . Solid curve 40 is a typical delay curve for a given rod size and rod orientation. It is understood

that the shape and extent of curve 40 will change in accordance with Equations 1 through 5 for any change in the parameters involved.

To this point, the description of the present invention has involved a straight rod. As seen from curve 40, a straight rod produces a delay characteristic which is substantially linear over a considerable extent of the operating range. In some instances, a delay characteristic which is more linear is desired; whereas in other instances a characteristic which is more nonlinear is preferred. It has been found that by bending rod 20, delay characteristics other than those predicted by Equation 1 result. For example, by bending rod 20 delay shapes such as shown by curves 41, 42 and 43 can be obtained. Thus the linearity of the delay characteristics of the embodiment of FIG. 2 can be substantially changed by bending rod 20 so that its axis is curved rather than straight. The orientation and curvature of the rod dictates the extent and shape of the delay characteristic.

In an adjustable structure, rod 20 has been bent to the desired curvature by means of a plurality of strings or threads attached to the rod at successive points. In one experimental embodiment, nylon string was utilized in order to minimize unwanted reflections and undesirable perturbation effects. These strings were then passed through guide 21 by means of small holes drilled in the wall. The desired delay characteristic was then obtained by pulling some or all of the strings in varying amounts to bend the rod correspondingly.

Where a nonadjustable structure is desired, the desired curvature can be obtained by bending rod 20 before it is mounted in guide 21 and supporting it in such bent position by means of dielectric spacers, or by imbedding the rod in polyfoam or by other means readily obvious to those skilled in the art.

Another simplified embodiment of the present invention is shown in the partially broken away pictorial view of FIG. 5. The embodiment of FIG. 5 is similar to that of FIG. 2 except that a section of rectangular waveguide

51 replaces circular waveguide 21. In FIG. 5 a conductive rod 50 extends longitudinally through guide 51 and slants from a point near the center of the guide at its entrance to a point near one of the narrow walls at its end. As in FIG. 2, the supporting means for rod 50 and the input means, have been omitted.

The solid lines 52 represent the electric field lines extending between the two broad surfaces of guide 51 when energy is propagated in the fundamental TE_{10} wave mode. In this instance it is preferable that the centerline of rod 50 lie in a plane midway between the two broad surfaces of guide 51 in order to minimize the possibility of mode conversion. In all other respects, the design of this embodiment is substantially the same as that of the embodiment of FIG. 2.

A more complete embodiment of the present invention is shown in the partially broken away pictorial view of FIG. 6. Like numerals have been carried over from FIG. 2, to designate like structural elements. In FIG. 6 a rectangular waveguide section 60 abuts at a right angle to guide 21. A plurality of tuning screws 61 are provided along one of the broad walls of guide 60 and along the wall of guide 21. An iris 70 is provided in guide 60 at the cross section where it abuts against guide 21.

Rod 20 is supported within guide 21 by means of supporting plates 62 and 63. Supporting plates 62 and 63 are each provided with an elongated slot 64 through which the ends of rod 20 pass. If the ends of rod 20 are first threaded, a nut 65 can be utilized at each end to hold the rod in its proper position. As is readily seen, the

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presence of the elongated slot 64 in supporting plates 62 and 63 allows the rod to be moved in the plane of symmetry to vary the values r_a and r_b , and therefore, the delay characteristic of the device.

A thin conductive septum 66 is slideably engaged with the walls of guide 21 and oriented so that its broad surface is perpendicular to the plane of symmetry. Septum 66 effectively short circuits the entrance end of guide 21 for energy propagating therein in the TE_{11} wave mode in the proper orientation. Thus, septum 66 prevents any of the incident or reflected energy from being radiated from the entrance end of guide 21; moreover, septum 66, in combination with iris 70 and tuning screws 61, also functions to match guide 60 to guide 21.

A plurality of nylon strings or threads 67 are attached to rod 20 at points spaced along its length. As mentioned above, the strings can be drawn uniformly or non-uniformly in order to deflect rod 20 and change the delay characteristic of the device. Strings 67 pass through small apertures in the wall of guide 21 in the plane of symmetry and are attached to screws 68. Screws 68 are threaded into a bar 69 which is attached to guide 21 by brackets or other suitable mounting means. In this manner, the tension in strings 67 can be adjusted individually by simply turning each of the screws 68. It is obvious that if rod deflection in the opposite direction is desired, the strings should pass through apertures on the opposite side of guide 21.

The use of strings to deflect rod 20 has proved satisfactory for experimental purposes. In the event, however, that a more permanent or rugged structure is desired, as mentioned above, other means such as dielectric spacers or a solid polyfoam cylinder can be utilized to deflect rod 20 within guide 21.

In operation, the signal to be delayed is fed into the input guide 60 by means of a circulator structure such as that shown in FIG. 1, in which case guide 60 corresponds to port 12 of the circulator 10, or by means of other suitable microwave hybrid networks well known in the art. The input wave energy, in the fundamental TE_{10} wave mode, then enters guide 21 and is transformed into the TE_{11} circular waveguide mode. This energy, as it propagates down guide 21 is reflected at successive cross sections depending upon its frequency, the lower frequency components being reflected near the input end and the higher frequency component being reflected near the far end of guide 21. The reflected wave energy is then extracted from the device through waveguide section 60, and coupled to the utilization means not shown.

In one particular experimental embodiment of the invention, a circular guide 21 having a length L of 59.45 inches and a radius r_g of 0.309 inch was utilized. A brass rod having a radius r_r of 0.055 inch was positioned inside the guide in the manner shown in FIG. 6. With r_a equal to 0.108 inch and r_b equal to 0.253 inch, a linear delay of 44.6 millimicroseconds was obtained over a frequency range extending between 10.80 and 11.48 kilomegacycles. A substantially linear delay curve, such as that shown in curve 42 of FIG. 4, was obtained by applying tension to three of the six nylon threads.

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In all cases it is understood that the above-described arrangement is merely illustrative of the application of the principles of the present invention. Numerous other arrangements including those using nonconductive rods or rods of other than circular cross section may be devised by those skilled in the art without departing from the spirit and scope of the present invention.

What is claimed is:

1. In combination, a hollow conductively bounded waveguiding structure, means for applying microwave energy having frequency components extending over a given band of frequency to a first end of said structure, means for progressively reflecting wave energy components of higher frequency as said wave energy propagates into said structure, said reflecting means comprising a rod extending from a region at said first end of said structure where the electric field has a large value to a region at the other end of said structure where said electric field has a smaller value, and means for extracting said reflected wave energy from said structure at said first end.

2. The combination according to claim 1 including additional means for deflecting said rod in the region between the two ends thereof.

3. A microwave delay network for selectively delaying the frequency components of broadband electromagnetic wave energy comprising, in combination, a hollow cylindrical waveguiding section, a rod extending obliquely within said section, the centerline of said rod lying in a plane with the axis of said section, means for propagating said wave energy into said structure at a first end thereof in the circular TE_{11} wave mode, the lines of maximum electric field in said mode being oriented perpendicular to said plane, and means for extracting reflected wave energy from said first end of said structure.

4. A delay network of claim 3 including additional means for deflecting said rod.

5. A delay network in accordance with claim 3 in which the rod is conductive, of circular cross section and of uniform thickness.

6. A microwave delay equalizer comprising, in combination, a microwave circulator, means for applying broadband electromagnetic wave energy to a first port of said circulator, means for extracting wave energy from a second port of said circulator, a delay network connected to the third port of said circulator for selectively delaying the frequency components of said wave energy, said delay network comprising, a hollow conductively bounded waveguiding structure, a rod extending obliquely within said structure, the centerline of said rod lying in a plane with the axis of said structure, and the lines maximum electric field of said wave energy being oriented perpendicular to said plane.

7. The delay equalizer according to claim 6 including additional means for deflecting said rod.

No references cited.

HERMAN KARL SAALBACH, *Primary Examiner*.

ROSS F. HUNT, *Assistant Examiner*.