

Jan. 14, 1958

S. D. ROBERTSON

2,820,170

SPATIAL HARMONIC TRAVELING WAVE TUBE

Filed Dec. 30, 1952

FIG. 1

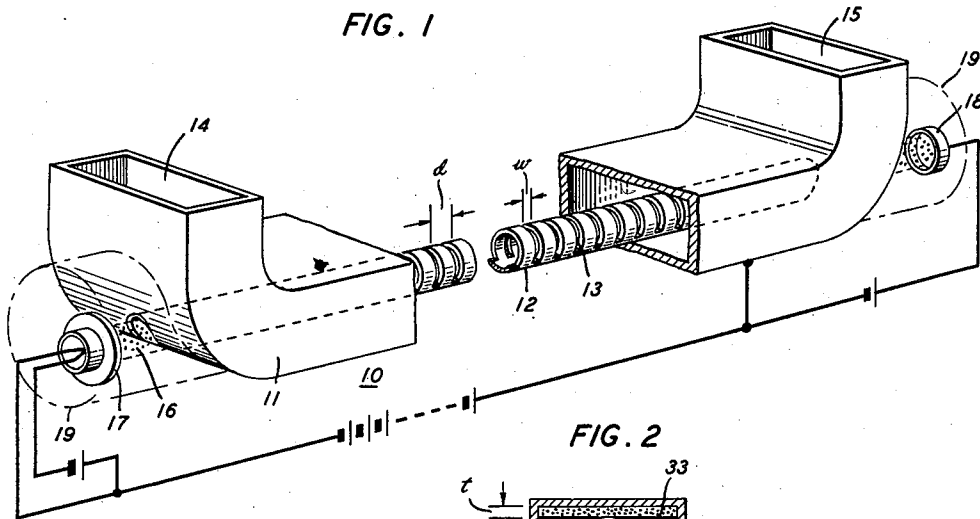


FIG. 2

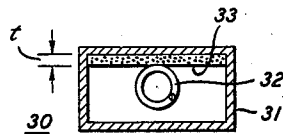
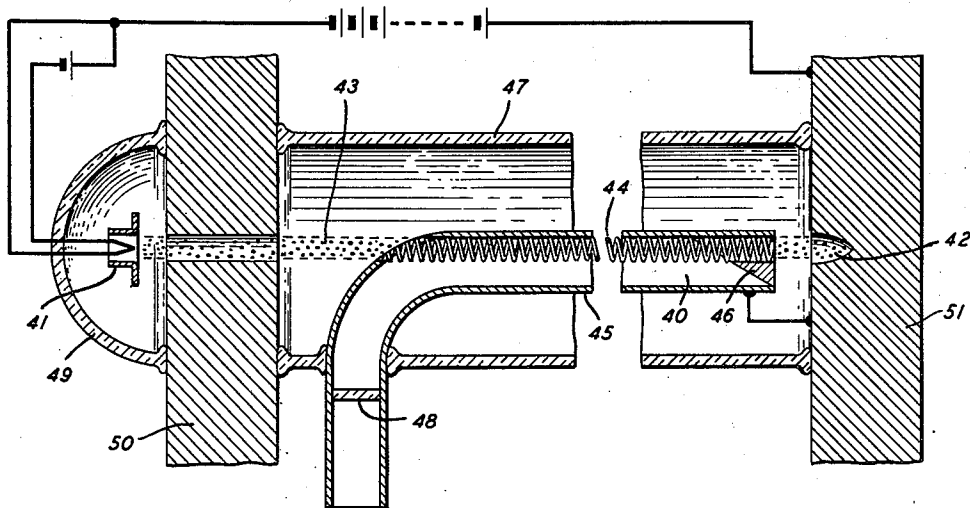


FIG. 3



INVENTOR
S. D. ROBERTSON
BY *Hugh S. Wentz*
ATTORNEY

1

2

2,820,170

SPATIAL HARMONIC TRAVELING WAVE TUBE

Sloan D. Robertson, Fair Haven, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application December 30, 1952, Serial No. 328,580

4 Claims. (Cl. 315—3.5)

This invention relates to microwave devices and more particularly to such devices of the so-called traveling wave type.

The principal object of this invention is to provide a wave propagating circuit for traveling wave tubes operating at extremely short wavelengths, which is relatively easy to manufacture and which is particularly well adapted for use with circular electron beams.

Another object is to achieve broad band amplification in traveling wave tubes operating at super high frequencies without sacrificing power dissipation capacity and simplicity of construction.

Helical traveling wave tubes, previous to this invention, have customarily amplified electromagnetic waves by surrounding an electron stream with a wire helix along which the waves propagate with an axial velocity substantially the same as the velocity of the electron stream so that the wave extracts kinetic energy from the electrons. Such a tube is admirably suited for operation at frequencies below, for instance, 10,000 megacycles, since it combines a very large band width with good gain while at the same time remains basically easy to manufacture. As the frequency of operation is increased, however, radiation from the propagating circuit becomes excessive unless the physical size of this element is proportionately decreased. At a frequency of 50,000 megacycles, for example, a conventional wire helix has a diameter roughly that of fine line pencil lead, and it is difficult, if not impossible, to distinguish the individual turns of wire with normal unaided eye-sight. As a consequence not only is such a helix very difficult to manufacture, but its power dissipation capacity is quite limited.

A solution to many of the problems encountered at these high frequencies is presented in an article "A Spatial Harmonic Traveling Wave Amplifier for Six Millimeters Wavelength" by S. Millman, appearing in the Proceedings of the Institute of Radio Engineers, volume 39, page 1040, September 1951. For a more complete explanation of the spatial harmonic principle of operation than that which follows the reader is referred to this article. Since, however, this principle is utilized in the present invention, a brief description of it will be given here.

If an electron stream is alternately shielded from and exposed to a component of field intensity in the same direction as that of a traveling electromagnetic wave, the wave can extract energy from the stream even though the wave travels at higher velocity, provided the alternate shielding occurs at the proper intervals. This is accomplished by beaming the electrons in electrical proximity to regularly spaced wave propagating discontinuities, chosen so that there exists between them a component of electric field parallel to the direction of electron flow and so that no such component exists in the region over them. By adjusting the velocity of the electron stream, a given electron can be made to reach each interval between discontinuities at a time when the electric field intensity at that point is the same as it was in the preceding interval when this electron arrived there. The electrons can thus be

synchronized in phase with any wave which propagates along these discontinuities with a component of phase velocity parallel to the direction of electron flow equal to the velocity of electrons, plus a velocity such that the electric field rotates any multiple of ± 360 degrees between successive intervals.

Tubes which have been built previous to now to incorporate the spatial harmonic principle represent a noticeable improvement over a conventional helical tube for millimeter wavelength since they are more rugged and offer better gain-band width product. None of them, however, is as easy to manufacture as might be desired and one purpose, therefore, of the present invention is to overcome this drawback.

In accordance with one aspect of this invention a wire helix, in conjunction with a conductively bounded wave guide, is adapted for use as a wave propagating circuit embodying the spatial harmonic principle. Such a structure incorporates many of the advantages of a conventional helical circuit and it offers additional advantages of its own. A clearer understanding, however, of this and of the other specific embodiments shown herein, together with a better appreciation of the general nature and objects of this invention, will best be gained from a study of the accompanying drawings and the following detailed description thereof.

With reference to the drawings in general:

Fig. 1 is a perspective view of an embodiment of a spatial harmonic wave guiding circuit in which the spatial harmonic discontinuities are formed by a plurality of transverse slot openings in a thin walled tube axially aligned with the direction of wave propagation within a rectangular wave guide;

Fig. 2 shows a cross section of the center portion of a second embodiment of a wave guiding circuit in which a rectangular wave guide surrounds a wire helix axially aligned with the guide and separated from one wall thereof by a sheet of dielectric material; and

Fig. 3 shows a side section of a backward wave oscillator in which the wave propagating circuit is a rectangular wave guide which includes within it a wire helix centered along the top wall of the guide.

Referring now more particularly to the drawings, Fig. 1 shows, by way of example for purposes of illustration, a spatial harmonic wave guiding circuit 10 which comprises a rectangular wave guide 11 within which a hollow cylindrical ridge, or tube, 12 is asymmetrically positioned. Cut through the wall of this ridge are a plurality of slot-like openings 13 which are regularly spaced in the direction of wave propagation and which, together with the metal between them, form a series of slot-resonators. These openings serve to expose recurrently the electrons, which may be beamed through the hollow center of tube 12, to the electric field of an electromagnetic wave propagating through circuit 10 in order that amplification of the wave may take place, as explained previously. They also serve to distort the electric field within the circuit so that a wave propagating in its fundamental transverse electric mode will have in their vicinity a component of electric field parallel to the electron flow.

The inside dimensions of guide 11 are preferably chosen so that a transverse electric wave may propagate there-through in its fundamental mode with the electric field perpendicular to the two wider walls of the guide. The straight center section of this guide surrounds ridge or tube 12 which may be brazed along the center of the lower wider wall. The wall thickness of this ridge is not critical but it should be many times the skin depth at the frequency of operation but still thin in comparison with the diameter of the ridge. The length of the slots cut through this wall should be roughly equal to a half free space wavelength at the upper cut-off frequency of the

circuit. For mechanical strength of the ridge, having openings as shown in Fig. 1, the circumference of the ridge should be slightly greater than this length. If desired, ridge 12 may be replaced by an equivalent wire helix having appropriate pitch and diameter. At both ends of tube 12 the guide is bent upward to provide impedance matching between the center section of the circuit and the input and output connections which may, for example, be wave guides of the same cross section as guide 11 connected directly to ends 14 and 15 of the circuit. Openings in the curved sections of the lower wall of guide 11 provide a free space for inserting tube 12 into the guide when the circuit is being assembled and they permit electron stream 16 to be beamed through the hollow center of this tube when the circuit is operating. Electron gun 17 and collector electrode 18 are aligned with respect to circuit 10 so that electron stream 16 which flows between them passes axially through tube 12. Identical envelopes 19 surround these electrodes and form, in conjunction with windows (not shown) in both ends of the guide and the metal walls thereof, an air-tight enclosure surrounding the electron stream. A magnetic field, produced by means not shown but which may be similar to magnets 50 and 51 shown in Fig. 3, is aligned with the axis of the electron stream for the purpose of confining the electrons to a small region around the axis of the stream. The conducting elements of circuit 10 should be non-magnetic in order not to distort the magnetic field and they should preferably have the same coefficient of expansion to minimize the effects of heating.

Wave energy is preferably applied to circuit 10 by some appropriate means so that the electric field of the wave propagates through the circuit perpendicular to the top wider wall of guide 11. As this wave propagates from the input end (end 14) of the circuit to the output end it is amplified by spatial harmonic interaction with the electron stream flowing through the center of tube 12. This spatial harmonic phenomenon has been dealt with briefly in the foregoing, but a better understanding of it will be gained by consideration of the following short mathematical analysis adapted specifically to the structure shown in Fig. 1 but applicable to spatial harmonic action in general.

If z is the direction of wave velocity in the wave guide, then in the vicinity of recurrent discontinuities in the guide the z component of a traveling wave may be written

$$E_z = F(z)e^{j\omega t} \quad (1)$$

in which ω is the radian frequency and

$$F(z) = \sum_{n=-\infty}^{n=\infty} A_n \exp \left[-j(2\pi n + \theta) \frac{z}{d} \right] \quad (2)$$

where d is the distance between successive discontinuities, which here are slots 13 in tube 12, n is an integer and θ is the phase delay in radians from one discontinuity to the next and is given by

$$\theta = \frac{2\pi d}{\lambda_g} \quad (3)$$

where λ_g is the guide wavelength of the fundamental wave corresponding to $n=0$ in Equation 2. Assuming the amplitude of E_z to be constant at the edge of the discontinuities or slots, and denoting it by E_0 , A_n may be written

$$\begin{aligned} A_n &= \frac{E_0}{d} \int_{-\frac{w}{2}}^{+\frac{w}{2}} \left[\exp \left(j(2\pi n + \theta) \frac{z}{d} \right) dz \right] \\ &= \frac{2E_0}{2\pi n + \theta} \sin \left[(2\pi n + \theta) \frac{w}{2d} \right] \end{aligned} \quad (4)$$

where w is the width of a slot 13 in tube 12. Substituting in Equation 1

$$E_z = E_0 \sum_{n=-\infty}^{n=\infty} \frac{2 \sin \left[(2\pi n + \theta) \frac{w}{2d} \right]}{2\pi n + \theta} \exp \left(j \left[\omega t - (2\pi n + \theta) \frac{z}{d} \right] \right) \quad (5)$$

From this last equation it can be seen that near the slot discontinuities in the wave guide there appears to be an infinite number of spatial harmonic components of the fundamental wave, each traveling at a different phase velocity given by

$$\frac{\omega d}{(2\pi n + \theta)}$$

in which n is an integer between $-\infty$ and $+\infty$. Setting $n=0$ we see that the fundamental wave travels in the positive z direction with a phase velocity of

$$\frac{\omega d}{\theta}$$

For $n=1$ a wave appears to travel in the positive z direction with a velocity of

$$\frac{\omega d}{(2\pi + \theta)}$$

which is less than the velocity for the fundamental wave. Similarly for other positive values of n . For $n=-1$, there appears to be a wave traveling in the positive z direction with a phase velocity

$$\frac{\omega d}{(-2\pi + \theta)}$$

which is negative since fundamental phase displacement θ between successive slots is less than 2π . Thus for each negative integer n there corresponds a wave having negative phase velocity, or, in other words, a backward traveling wave. The group velocity of all spatial harmonic waves, it should be remembered, is always in the direction of power propagation and is the same for all, including those which have negative phase velocity.

From an inspection of Fig. 1 it is apparent that somewhere between the condition where the slot spacing d is zero, in which case there is substantially no interaction between the electromagnetic wave and the electron stream, and the condition where width w of slot opening is zero, in which case the interaction is likewise zero, there must be some ratio of slot width to slot spacing which gives optimum interaction if there is to be any net gain. Now, it is easily shown that the electron velocity V_e required for synchronization is given by

$$V_e = \frac{\omega d}{(2\pi n + \theta)} \quad (6)$$

where ω is the radian frequency, d center to center slot spacing, n an integer and θ the fundamental phase displacement between slots, usually

$$\frac{\pi}{3} \text{ to } \frac{\pi}{2}$$

It can further be shown that the amplification of the electromagnetic wave interacting with the electrons is proportional to

$$\text{Gain} = K \frac{\sin^2 \left[(2\pi n + \theta) \frac{w}{2d} \right]}{(2\pi n + \theta) \frac{w}{2d}} \quad (7)$$

where K is a proportionality constant and where w is the width of a slot opening. By differentiating this last equation with respect to w/d and setting the result equal to zero, the gain is seen to be maximum when

$$\frac{w}{d} = \frac{2.33}{(2\pi n + \theta)} \quad (8)$$

As mentioned previously, practical values of θ may be roughly between

$$\frac{\pi}{3} < \theta < \frac{\pi}{2}$$

5

and so from Equations 6 and 8 w is easily determined for a given electron velocity V_e , a given value of n and a given frequency of operation.

The optimum slot-spacing and slot width of a structure designed for a particular mode of spatial harmonic operation is determined from Equations 6 and 8 but it should be understood that this same structure may be used for operation in additional modes although with somewhat reduced efficiency. The number of slots used will depend upon the gain desired but approximately 100 are ordinarily sufficient. The following dimensions will serve to indicate the size relationships of the various elements of the structure shown in Fig. 1. Although these dimensions have been found satisfactory in a circuit substantially the same as that in Fig. 1 which has been built and tested, they are not given in limitation but merely in illustration of possible values. These dimensions have been chosen for optimum interaction of the first spatial harmonic of a wave with an electron stream having a velocity roughly equivalent to 1300 volts. The inside width and height of guide 11 are $0.83\lambda_0$ and $0.41\lambda_0$, length of slot 13= $0.46\lambda_0$, width $w=0.027\lambda_0$, distance $d=0.086\lambda_0$, where λ_0 is the free space wavelength at the frequency of operation.

Fig. 2 shows a cross section of a center portion of a wave guiding circuit 30 which is similar in operation to that shown in Fig. 1. Circuit 30 consists of a rectangular wave guide 31, which may be, but is not necessarily, identical to guide 11 in Fig. 1, which surrounds wire helix 32. This helix, which is separated from a wider wall of the guide 31, corresponding to the lower wall of guide 11, by a sheet of dielectric 33, may be thought of as equivalent to ridge 12 in Fig. 1. The pitch between turns of helix 32 corresponds to distance d and the opening between turns corresponds in width to width w of the openings in ridge 12. The presence of dielectric material 33, which may for example be mica, permits the diameter of helix 32 to be approximately twice the diameter that ridge 12 may be made for a given frequency of operation. Thickness t of this dielectric, which is preferably uniform along the length of the guide in order that helix 32 may be aligned parallel to the axis thereof, may be chosen from a range having wide limits but a value of roughly one-tenth the diameter of helix 32 has been found satisfactory. The result of decreasing thickness t is to lower the frequency of operation for a given helix and wave guide. The turns of wire forming helix 32, together with the spaces between them, form a series of slot-resonators which are substantially the same as the resonators in Fig. 1. It is therefore apparent that helix 32 may be replaced by a plurality of loops of wire which are transverse to the direction of wave propagation and regularly spaced a distance d apart in that direction.

In operation, an electron stream may be beamed through the center of helix 32 and a transverse electric wave may be applied to circuit 30 by an appropriate means, such as the curved end of guide 11 in Fig. 1. Wave energy may then be extracted at the output end of the circuit by some suitable means.

The wire helix shown in Fig. 2, as well as the parallel loop structure, is particularly adapted to backward spatial harmonic operation, since the ratio of space between the wire w to the wide pitch d can readily be made to satisfy Equations 6 and 8 for negative integers. A ratio of

$$\frac{w}{d} = \frac{1}{2}$$

has been found suitable in such a structure for synchronization of the electron stream with the first backward wave. A smaller ratio in the vicinity of one-third should be used with the first forward wave.

It should be understood that none of the wave guiding circuits described in the foregoing is limited to spatial harmonic wave amplification since any of these struc-

6

tures, if it has the required dimensions, may be used for the generation of wave energy either by conventional or by backward wave operation. Conventional oscillations may be obtained in any amplifier simply by returning a sufficient portion of the output energy to the input of the amplifier and the operation of such an arrangement is so well known that more of a description here would be superfluous. The generation of backward wave oscillations on the other hand is a recent development in the art and in view of the importance of the present invention in this regard, a brief description of the backward wave oscillator is appropriate.

In Fig. 3 there is shown a side section of a backward wave oscillator in which circuit 40 is the wave propagating element. This circuit is aligned with respect to electron gun 41 and collector cavity 42 so that electron stream 43 flows through the center of helix 44 which may be brazed along the center of the top wider wall of rectangular guide 45. At the collector end of the circuit, lossy material 46 is positioned within guide 45 surrounding helix 44, in order to minimize reflection of wave energy at this point. Any wave energy which may be returned from the output connection at the gun end of the circuit by impedance mismatches there is thus substantially reduced and its unwanted interference with energy propagating in the opposite direction is mostly eliminated. At the gun end of the circuit oscillating wave energy is extracted from the circuit by a continuation of guide 45 which is bent downward for impedance matching as explained previously. An appropriate opening is provided in the curved section of the top wall of this guide for the passage of electron stream 43. Guide 45 is sealed through envelope 47 and this envelope, together with window 48 in the guide, envelope 49 and magnet poles 50 and 51, form a gas-tight enclosure surrounding the electron stream. Opening 42 in pole piece 51 is shaped approximately as shown in order to reduce secondary emission from this member which serves additionally as the collector electrode. All the elements in the region between pole pieces should be nonmagnetic so that the magnetic field may be made to focus the electron stream along an axis with which the field is aligned.

When the current density of electron stream 43 in the arrangement shown in Fig. 3 exceeds a certain critical value, oscillations may suddenly begin at a frequency which is determined by stream velocity. Wave energy originating at the collector end of circuit 40 flows toward the output end thereof, where it is led off through window 48 to an appropriate output connection. As this energy passes along the helix within guide 45 it is amplified by interaction between the backward traveling spatial harmonic of itself which is synchronized with the electron stream. This interaction at the same time causes a bunching of the electron stream. This bunching in turn causes an increase in wave energy which in turn causes a bunching of the electron stream and so on. Thus the feedback energy necessary to sustain oscillations is automatically returned to the circuit by the electron stream. Since the frequency of oscillation is determined principally by the electron stream velocity for a given wave guiding structure and since this velocity is easily varied over a wide range, the frequency may be modulated at a high rate and over a very broad band width.

The invention described herein is not limited solely to the embodiments shown or described, since it may include wave guides of other than rectangular cross section. Furthermore, the input and output connections described above in connection with the drawings may be replaced by equivalent means without altering the nature of this invention. Lastly, it will be apparent to those skilled in the art that the dimensions of the wave guiding circuits shown in the accompanying drawings may be selected over a wide range without departing from the spirit or scope of the invention as set forth.

7

What is claimed is:

1. In a microwave device, means for beaming an electron stream along a path, and wave guiding means adapted to propagate therethrough in a direction parallel to said path an electric wave for interaction with said electron stream, said wave guiding means including a wave guide asymmetrically surrounding a hollow cylindrical ridge having cut in its surface a plurality of slot-resonators lying transverse to the direction of wave propagation and regularly spaced in that direction, the lateral dimensions of said ridge being less than the lateral dimensions of said wave guide.

2. In a traveling wave tube, means for forming and projecting an electron stream, and conductively bounded wave guiding means including a hollow cylindrical tube connected along one wall within a rectangular wave guide and spaced from the remaining walls thereof and having in its surface a plurality of slot-like openings transverse to the direction of wave propagation and regularly spaced apart in that direction.

3. In a traveling wave tube, means for forming and projecting an electron stream, and conductively bounded wave guiding means including a length of rectangular wave guide whose ends are bent out of the line of the electron flow and whose center section surrounds a hollow cylindrical member lying along one wall and spaced from the remaining walls thereof whose surface contains a

8

plurality of slots forming slot-resonators lying substantially transverse to the direction of wave propagation and which are regularly spaced in that direction.

4. In a microwave device, means adapted to propagate therethrough an electromagnetic wave at a speed less than the speed of light, said means including a raised cylindrical hollow ridge having cut in the surface thereof a plurality of slot-like openings lying substantially transverse to the direction of wave propagation and spaced apart in that direction, and a rectangular wave guide asymmetrically surrounding said ridge, said ridge being spaced from at least three walls of said wave guide.

References Cited in the file of this patent**UNITED STATES PATENTS**

2,395,560	Llewellyn	Feb. 26, 1946
2,567,748	White	Sept. 11, 1951
2,590,511	Craig et al.	Mar. 25, 1952
2,623,121	Loveridge	Dec. 23, 1952
2,641,731	Lines	June 9, 1953
2,647,175	Sheer	July 28, 1953
2,708,236	Pierce	May 10, 1955

OTHER REFERENCES

Article by J. R. Pierce, entitled "Millimeter Waves," pp. 24-29 of "Physics Today," for Nov. 1950.