

Dec. 11, 1945.

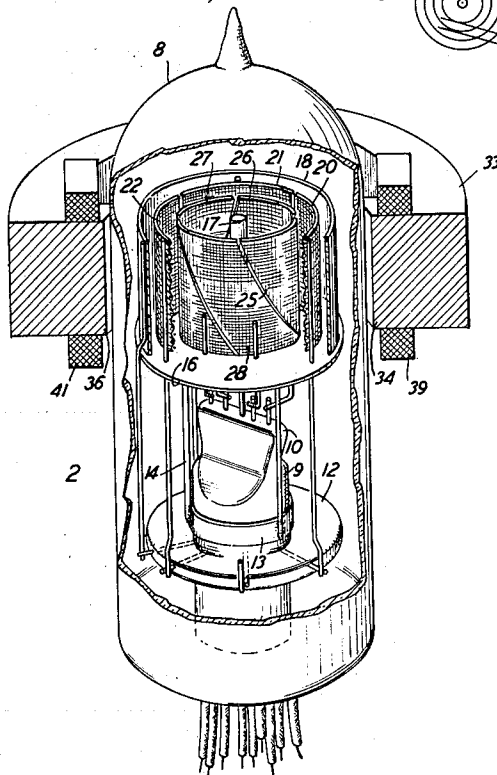
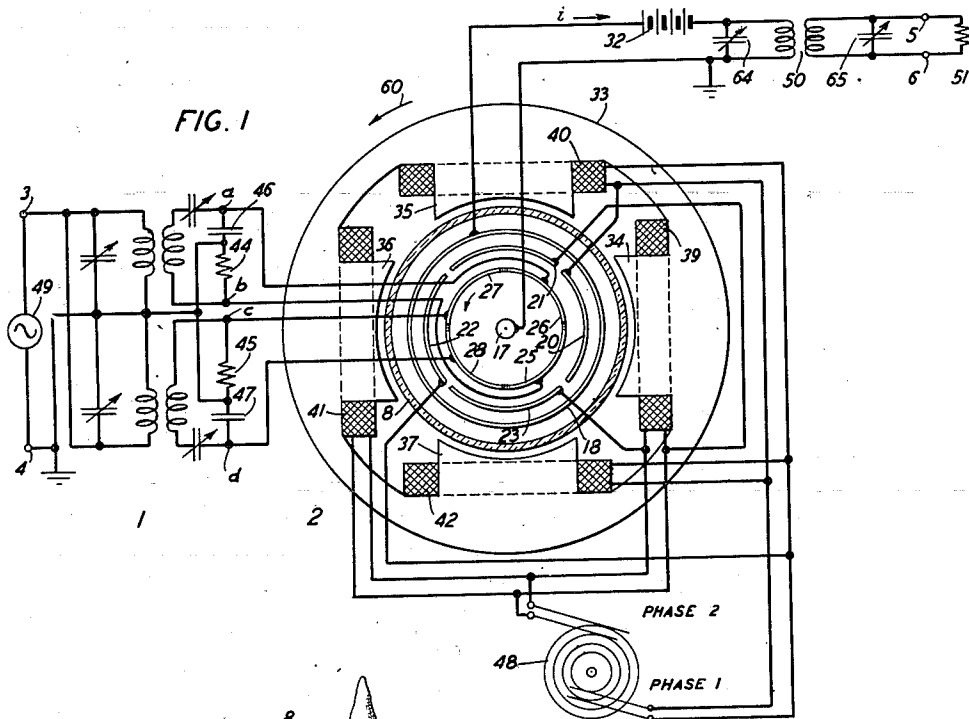
K. G. JANSKY

2,390,884

PHASE SHIFTER

Filed Nov. 15, 1943

2 Sheets-Sheet 1



INVENTOR
K. G. JANSKY
BY
Ralph P. Holcomb
ATTORNEY

Dec. 11, 1945.

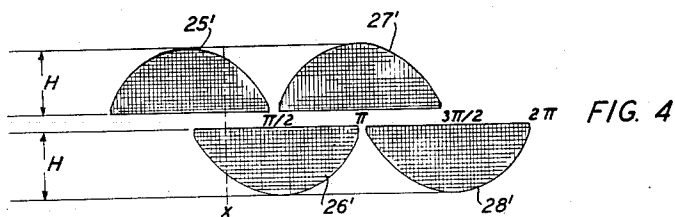
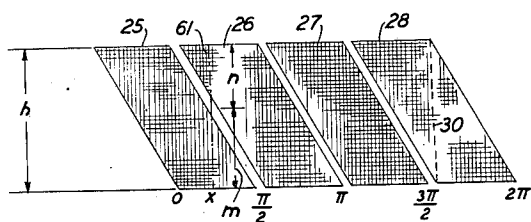
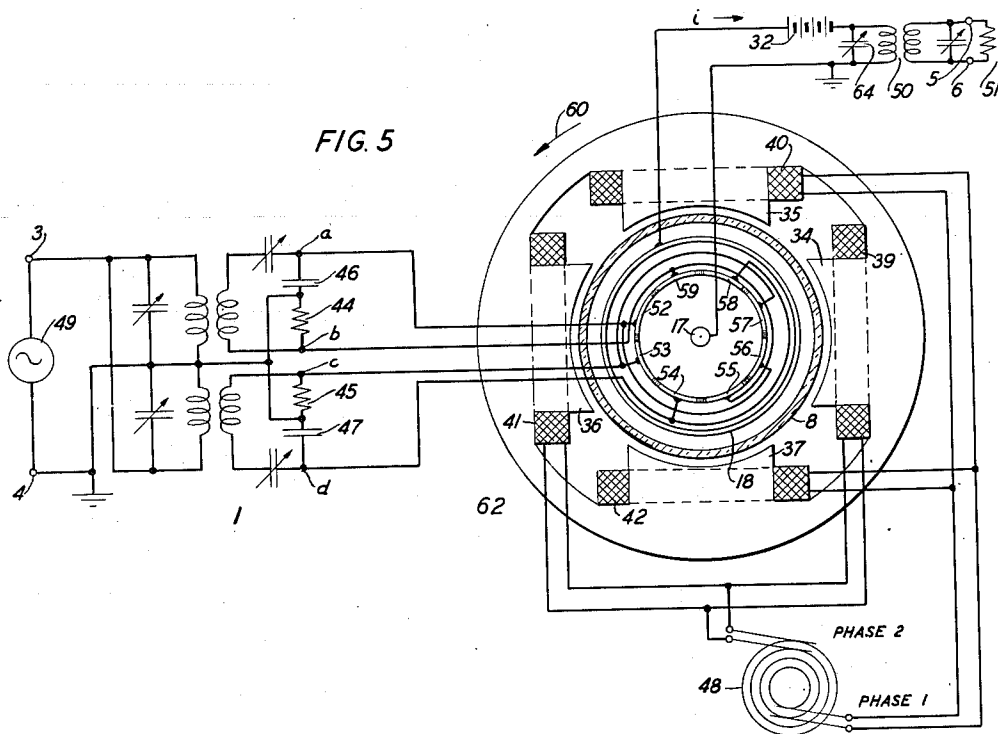
K. G. JANSKY

2,390,884

PHASE SHIFTER

Filed Nov. 15, 1943

2 Sheets-Sheet 2



INVENTOR

K. G. JANSKY

BY

Ralph T. Holcomb

ATTORNEY

UNITED STATES PATENT OFFICE

2,390,884

PHASE SHIFTER

Karl G. Jansky, Little Silver, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application November 15, 1943, Serial No. 510,357

20 Claims. (Cl. 315—14)

This invention relates to phase shifters and more particularly to a variable phase shifter of the electronic type.

The principal object of the invention is to shift the phase of an output current with respect to the input current. A further object is to provide a variable phase shifter without mechanically moving elements. Another object is to shift the phase very rapidly. Another object is to shift the phase at a uniform rate. Still a further object is to maintain the output current constant as the phase is shifted.

The phase shifter in accordance with the invention comprises a phase splitter and an electron tube of the rotary beam type. The tube includes a linear cathode and a cylindrical anode coaxial therewith. Between the cathode and the anode are a number of control grids so shaped and so positioned that each grid overlaps the two adjacent grids in the direction parallel with the longitudinal axis of the cathode. Suppressor grids may be inserted in the tube between the control grids and the anode, permitting only a single beam to be formed between the cathode and the anode. The phase splitter provides four quadrantal voltages which are impressed upon the control grids. The beam, as it rotates, is at all times focused upon the control grids. The relative phase of the alternating component of the anode current is dependent upon the angular position of the beam.

There is thus provided a rapidly variable phase shifter which requires no mechanically moving elements. If the control grids are so shaped that one edge follows a sine curve, the phase shift will be proportional to the angular displacement of the rotary beam and if the beam is rotated at a uniform rate the phase will be shifted at a uniform rate. This special grid shape has the further advantage that the anode current will be constant in magnitude regardless of the phase shift. The suppressor grids may be eliminated if the number of control grids is doubled.

The nature of the invention will be more fully understood from the following detailed description and by reference to the accompanying drawings, in which like reference characters refer to similar or corresponding parts and in which

Fig. 1 is a schematic circuit showing one embodiment of the variable phase shifter of the invention;

Fig. 2 is a perspective view, partly cut away, of the rotary beam tube used in the circuit of Fig. 1;

Fig. 3 shows, unrolled, the control grids used in the tube of Figs. 1 and 2;

Fig. 4 shows sinusoidally shaped control grids which may be used in place of those shown in Fig. 3; and

Fig. 5 is a schematic circuit showing another embodiment of the invention in which the suppressor grids are eliminated but the number of control grids is doubled.

As shown by the schematic circuit of Fig. 1, one embodiment of the variable phase shifter in accordance with the invention comprises a phase splitting circuit 1 and a rotary beam electron tube 2 connected between input terminals 3, 4 and output terminals 5, 6. As shown more clearly in the perspective view of Fig. 2, the tube 2 comprises a highly evacuated enclosing vessel 8 at one end of which there is an internal stem 9 terminating in a press 10 and having intermediate its ends an annular flange 12. Clamped about the stem 9 is a metallic band 13 to which are affixed a plurality of rigid metallic supports 14 to the upper ends of which is attached an insulating disc 16 which mounts the electrodes.

The electrodes include a linear cathode 17, which may be indirectly heated by a heater element, not shown. The anode 18 is in the form of a metallic cylinder which surrounds the cathode 17 and is coaxial therewith. Between the cathode 17 and the anode 18 are four arcuate suppressor grids 20, 21, 22 and 23, spaced from each other to form a segmented cylinder, also concentric with the cathode 17. Between the cathode 17 and the suppressor grids 20, 21, 22 and 23 are four arcuate control grids 25, 26, 27 and 28 spaced from each other to form a second segmented cylinder also concentric with the cathode 17. When unrolled, as shown in Fig. 3, the control grids 25, 26, 27 and 28 are parallelograms so proportioned that a line, such as 30, from the lower left corner to the upper right corner will divide the grid into two right-angled triangles. As shown more clearly in Fig. 2, each control grid overlaps the two adjacent ones in the direction parallel with the longitudinal axis of the cathode 17 for a distance approximately equal to half the width of the grid. The grid 28, for example, overlaps the grid 25 on the right and the grid 27 on the left.

The anode 18 is maintained at a moderately high positive potential with respect to the cathode 17 by means of the battery 32 which establishes a radial electrostatic field therebetween. A continuously and uniformly rotating magnetic field, with the lines of force normal to the longitudinal axis of the cathode 17, is also established. This

magnetic field is provided by surrounding the envelope 8 by a magnetic core 23 having four equally spaced poles 34, 35, 36 and 37, which carry the coils 39, 40, 41 and 42, respectively. Diametrically opposite coils, such as 39 and 41, are connected and poled so that opposite poles, such as 34 and 36, are opposite in polarity. As shown in Fig. 1 excitation is provided by connecting the two opposite coils 40 and 42 to one phase and the other two coils 39 and 41 to the other phase of a two-phase alternator 43.

As explained more fully in United States Patent 2,217,774, issued October 15, 1940, an electron tube of the type described above may be designed to provide a uniformly rotating electron beam which may be focused as desired. In the tube 2, the beam is focused upon one or more of the control grids 25, 26, 27 and 28. If suppressor grids are not employed, there will be two beams produced which are projected in opposite directions from the cathode 17 to the anode 18. However, since the tube 2 has only four control grids one of these beams must be suppressed. This is the function of the suppressor grids 20, 21, 22 and 23. If the two diametrically opposite suppressor grids 20 and 22 are connected in opposite polarity to the first phase of the alternator 43 and the remaining two suppressor grids 21 and 23 are connected in opposite polarity to the second phase, as shown in Fig. 1, one of the beams will be suppressed.

The function of the phase splitter 1 is to provide at the points *a*, *b*, *c* and *d* four equal quadrantal voltages to ground, that is, voltages which are 90 degrees, or $\pi/2$ radians, apart. Any suitable circuit may be used for this purpose. The one shown is of the type shown and described on page 357 of the Bell System Technical Journal for July, 1937, and need not be described in detail here. In order to make the voltages equal the resistors 44 and 45 are made equal, the capacitors 46 and 47 are made equal and the reactance of each capacitor is made equal in magnitude to the resistance of each resistor at the frequency *f* of the source 43 connected to the input terminals 3 and 4. The points *a*, *b*, *c* and *d* are connected, respectively, to the control grids 26, 25, 27 and 28 so that the control grids have impressed upon them four equal quadrantal voltages.

The output voltage of the phase shifter is obtained across the secondary of the transformer 50, the primary of which is connected between the cathode 17 and the anode 18. The transformer 50 is tuned by means of the variable capacitors 54 and 55 to pass the frequency *f*. Any suitable load, indicated schematically as the impedance 51, may be connected to the output terminals 5 and 6.

The amplitude and relative phase of the alternating component of the anode current *i* will now be considered, assuming that the control grids 25, 26, 27 and 28 are parallelograms, as shown in Fig. 3, and neglecting the small spacing between grids. If the electron beam passes through only one control grid, the phase of *i* will correspond to the phase of the voltage on that grid. For example, if the beam passes through the point 0 in the grid 25, the phase of *i* will be the same as the phase of the voltage on the grid 25. However, if part of the beam passes through one grid and another part passes through an adjacent grid, then the amplitude and phase of *i* will be determined by the propor-

tion of the beam that goes through each of the two grids.

It will be assumed that the beam is rotating in a counter-clockwise direction, as indicated by the arrow 60 in Fig. 1. The angular departure of the beam from its reference position at 0, in radians, will be denoted by *x*. If *x* falls between 0 and $\pi/2$ the beam will have some position such as is indicated in Fig. 3 by the dot and dash line 61 and the current *i* will be made up of two components, *i*₁ contributed by that part of the beam which passes through the grid 25 and *i*₂ contributed by the part which goes through the grid 26. That is,

$$i = i_1 + i_2 \quad (1)$$

The amplitude of *i*₁ will be proportional to the length *m* of the intercept on the grid 25, given by

$$m = h \left(1 - \frac{2x}{\pi} \right) \quad (2)$$

where *h* is the height of the grids. Therefore, the component *i*₁ at any harmonic time *t* seconds is given by

$$i_1 = kh \left(1 - \frac{2x}{\pi} \right) \cos \omega t \quad (3)$$

where *k* is a constant which is a function of the tube parameters and the amplitude of the grid voltage, but is independent of *x*, and ω is the angular velocity of the source 43 in radians per second, equal to $2\pi f$. In like manner, the amplitude of *i*₂ will be proportional to the length *n* of the intercept on the grid 26, where

$$n = \frac{2hx}{\pi} \quad (4)$$

and therefore *i*₂ may be expressed as

$$i_2 = \frac{2khx}{\pi} \cos \left(\omega t + \frac{\pi}{2} \right) \quad (5)$$

Then, from Equations 1, 3 and 5,

$$i = kh \left(1 - \frac{2x}{\pi} \right) \cos \omega t + \frac{2khx}{\pi} \cos \left(\omega t + \frac{\pi}{2} \right) \quad (6)$$

But

$$\cos \left(\omega t + \frac{\pi}{2} \right) = -\sin \omega t \quad (7)$$

50 and

$$A \cos \theta - B \sin \theta$$

$$= \sqrt{A^2 + B^2} \left(\frac{A \cos \theta}{\sqrt{A^2 + B^2}} - \frac{B \sin \theta}{\sqrt{A^2 + B^2}} \right) \quad (8)$$

$$= \sqrt{A^2 + B^2} (\cos \phi \cos \theta - \sin \phi \sin \theta) \quad (9)$$

$$= \sqrt{A^2 + B^2} \cos (\theta + \phi) \quad (10)$$

where

$$\phi = \tan^{-1} \frac{B}{A} \quad (11)$$

and therefor

$$A \cos \theta - B \sin \theta = \sqrt{A^2 + B^2} \cos \left(\theta + \tan^{-1} \frac{B}{A} \right) \quad (12)$$

Now, applying Equations 7 and 12 and letting

$$A = kh \left(1 - \frac{2x}{\pi} \right) \quad (13)$$

$$B = \frac{2khx}{\pi} \quad (14)$$

and

$$\theta = \omega t \quad (15)$$

Equation 6 may be written

$$i = \sqrt{k^2 h^2 \left(1 - \frac{2x}{\pi}\right)^2 + \left(\frac{2khx}{\pi}\right)^2} \cos \left[\omega t + \tan^{-1} \frac{2khx}{\pi kh \left(1 - \frac{2x}{\pi}\right)} \right] \quad (16)$$

$$i = \frac{2kh}{\pi} \sqrt{\left(\frac{\pi}{2} - x\right)^2 + x^2} \cos \left(\omega t + \tan^{-1} \frac{x}{\frac{\pi}{2} - x} \right) \quad (17)$$

Similar equations may be derived for the current i when x is greater than $\pi/2$. Thus, if x falls between $\pi/2$ and π

$$i = \frac{2kh}{\pi} \sqrt{(\pi - x)^2 + \left(x - \frac{\pi}{2}\right)^2} \cos \left(\omega t + \frac{\pi}{2} + \tan^{-1} \frac{x - \frac{\pi}{2}}{\pi - x} \right) \quad (18)$$

for x between π and $3\pi/2$

$$i = \frac{2kh}{\pi} \sqrt{\left(\frac{3\pi}{2} - x\right)^2 + (x - \pi)^2} \cos \left(\omega t + \pi + \tan^{-1} \frac{x - \pi}{\frac{3\pi}{2} - x} \right) \quad (19)$$

and for x between $3\pi/2$ and 2π

$$i = \frac{2kh}{\pi} \sqrt{(2\pi - x)^2 + \left(x - \frac{3\pi}{2}\right)^2} \cos \left(\omega t + \frac{3\pi}{2} + \tan^{-1} \frac{x - \frac{3\pi}{2}}{2\pi - x} \right) \quad (20)$$

It will be seen from Equations 17, 18, 19 and 20 that the phase of the current i increases through an angle of 2π radians, or 360 degrees, as the beam makes one rotation about the cathode 17 but that the phase change is not a linear function of the angle x . As given by Equation 17, the phase change in the first quadrant is equal to

$$\tan^{-1} \frac{x}{\frac{\pi}{2} - x}$$

and the maximum deviation from linearity will be a little more than 4 degrees. The maximum deviation in the other quadrants will be the same. Furthermore, the amplitude of i is not independent of x and in the first quadrant, for example, is equal to

$$\frac{2kh}{\pi} \sqrt{\left(\frac{\pi}{2} - x\right)^2 + x^2}$$

However, if the grids 25, 26, 27 and 28 are replaced by the grids 25', 26', 27' and 28', shown unrolled in Fig. 4, so shaped that one edge follows a sine curve while the other edge is a straight line, the current i for values of x falling in the first quadrant is given by the equation

$$i = KH \sqrt{\sin^2 x + \cos^2 x} \cos \left(\omega t + \tan^{-1} \frac{\sin x}{\cos x} \right) \quad (21)$$

$$= KH \cos(\omega t + x) \quad (22)$$

where K is a function of the tube parameters and the amplitude of the grid voltages, but is independent of x , and H is the maximum height of each grid. With grids of this shape, it is seen from Equation 22 that, in the first quadrant, the magnitude of i is independent of x and the phase shift is exactly equal to x . Expressions similar to (22) may be derived for the other quadrants

which will show that these same conditions hold for any value of x .

Fig. 5 shows schematically a variable phase shifter in accordance with the invention in which the suppressor grids 20, 21, 22 and 23 have been eliminated. In this case there will be no suppression of the electron beam and the two beams will be projected in opposite directions from the cathode 17 to the anode 18. It is necessary, therefore, to double the number of control grids in the rotary beam tube 62. Accordingly, the four control grids 25, 26, 27 and 28 of Fig. 1 are replaced in the tube 62 by eight control grids 52 to 59, inclusive, of the type shown in Fig. 3. Diametrically opposite control grids are connected to the same point in the phase splitter 1. As shown, the control grids 52 and 56 are connected to the point a , 55 and 59 to b , 53 and 57 to c and 54 and 58 to d . The circuit of Fig. 5 will, therefore, have a phase shift of 720 degrees for each complete rotation of the beams. The other parts of the circuit of Fig. 5 are the same as shown and described in connection with Fig. 1. Of course, control grids of the sinusoidal type, such as are shown in Fig. 4, may be substituted for those of the parallelogram type, as explained above in connection with Fig. 1, to provide a current i which will be constant in magnitude and the relative phase of which will vary linearly with the angle of displacement of the electron beams.

What is claimed is:

1. A variable phase shifter comprising a rotary beam electron tube which includes a linear cathode, a cylindrical anode concentric with said cathode, a plurality of control grids spaced from each other and so shaped and positioned that said grids form a segmented cylinder concentric with said cathode between said cathode and said anode and means for impressing equal quadrantal voltages upon said grids, each of said grids overlapping the two adjacent grids in a direction parallel with the longitudinal axis of said cathode.
2. A phase shifter in accordance with claim 1 in which the electron beam is focused upon said grids.
3. A phase shifter in accordance with claim 1 in which each of said grids overlaps an adjacent grid for a distance approximately equal to half the width of said grid.
4. A phase shifter in accordance with claim 1 which includes a plurality of arcuate suppressor grids positioned between said control grids and said anode to form a segmented cylinder coaxial with said cathode.
5. A phase shifter in accordance with claim 1 in which each of said grids when unrolled is a parallelogram so proportioned that a line from a lower corner to an upper corner will divide said grid into two right-angled triangles.
6. A phase shifter in accordance with claim 1 in which each of said grids when unrolled is so shaped that one edge follows a sine curve.
7. A phase shifter in accordance with claim 1 in which the electron beam is focused upon said grids and each of said grids when unrolled is so shaped that one edge follows a sine curve.
8. A phase shifter in accordance with claim 1 in which each of said grids overlaps an adjacent grid for a distance approximately equal to half the width of said grid and when unrolled is so shaped that one edge follows a sine curve.
9. A phase shifter in accordance with claim 1 which includes a plurality of arcuate suppressor grids positioned between said control grids and

said anode, each of said control grids when unrolled being so shaped that one edge follows a sine curve.

10. A phase shifter in accordance with claim 1 in which the electron beam is focused upon said grids and each of said grids overlaps an adjacent grid for a distance approximately equal to half the width of said grid.

11. A phase shifter in accordance with claim 1 which includes a plurality of arcuate suppressor grids positioned between said control grids and said anode, each of said control grids overlapping an adjacent control grid for a distance approximately equal to half the width of said control grid.

12. A phase shifter in accordance with claim 1 which includes a plurality of arcuate suppressor grids positioned between said control grids and said anode, the electron beam being focused upon said control grids.

13. A phase shifter in accordance with claim 1 which includes a plurality of arcuate suppressor grids positioned between said control grids and said anode, each of said control grids when unrolled being so shaped that one edge follows a sine curve and the electron beam being focused upon said control grids.

14. A phase shifter in accordance with claim 1 in which the electron beam is focused upon said grids, each of said grids when unrolled is so shaped that one edge follows a sine curve, and each of said grids overlaps an adjacent grid for

a distance approximately equal to half the width of said grid.

15. A variable phase shifter comprising means for deriving four equal quadrantal voltages from an alternating source, means for producing a rotating electron beam, a cylindrical anode upon which said beam impinges, four arcuate control grids located in the path of said beam and means for impressing said voltages respectively upon said grids, each of said grids overlapping the two adjacent grids in a direction parallel with the longitudinal axis of said anode.

16. A phase shifter in accordance with claim 15 in which said beam is focused upon said control grids.

17. A phase shifter in accordance with claim 15 in which each of said grids overlaps an adjacent grid for a distance approximately equal to half the width of said grid.

18. A phase shifter in accordance with claim 15 which includes a plurality of arcuate suppressor grids positioned between said control grids and said anode.

19. A phase shifter in accordance with claim 15 in which each of said grids when unrolled is a parallelogram so proportioned that a line from a lower corner to an upper corner will divide said grid into two right-angled triangles.

20. A phase shifter in accordance with claim 15 in which each of said grids when unrolled is so shaped that one edge follows a sine curve.

KARL G. JANSKY.