Dec. 4, 1951 W. E. KOCK 2,577,619

METALLIC STRUCTURE AND DELAYING UNIPOLARIZED WAVES

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FIG. 1

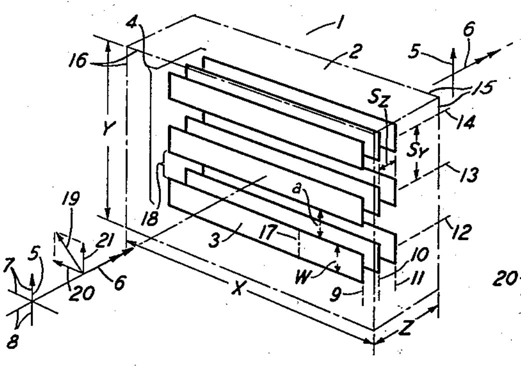


FIG. 3

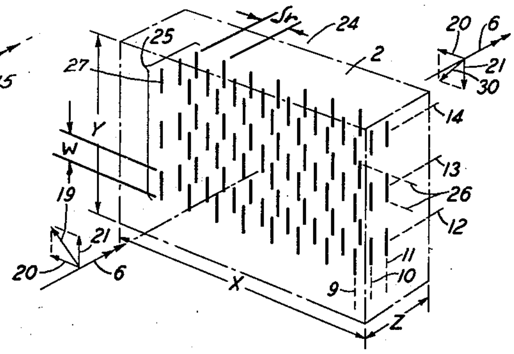


FIG. 2

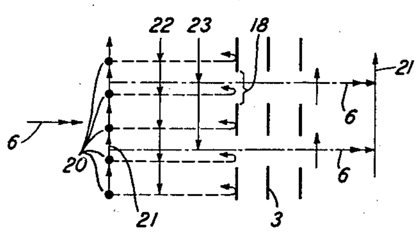


FIG. 4

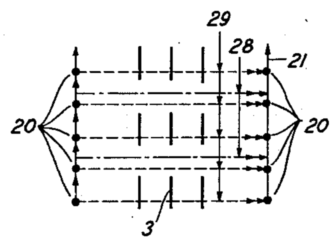


FIG. 15

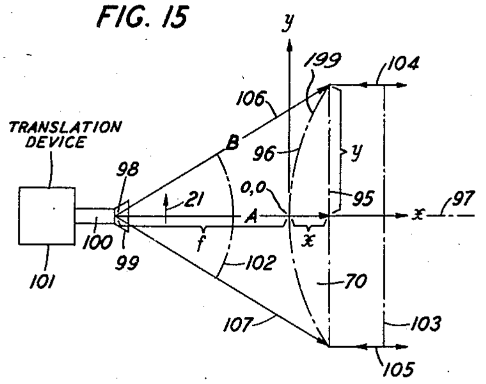
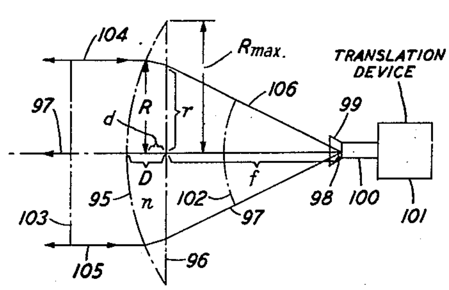


FIG. 16 (PRIOR ART)



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METALLIC STRUCTURE AND DELAYING UNIPOLARIZED WAVES

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FIG. 5

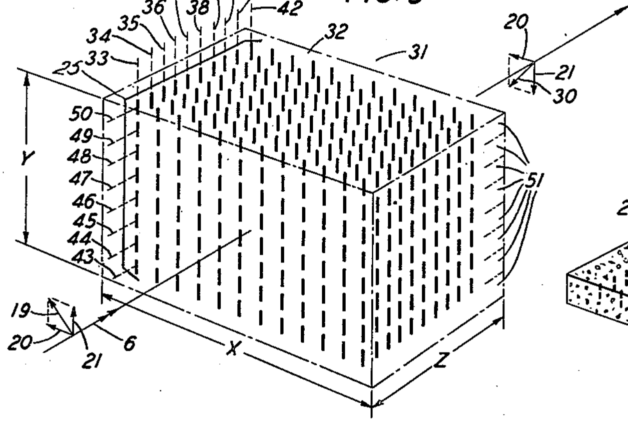


FIG. 6

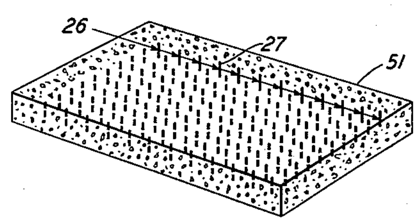


FIG. 7

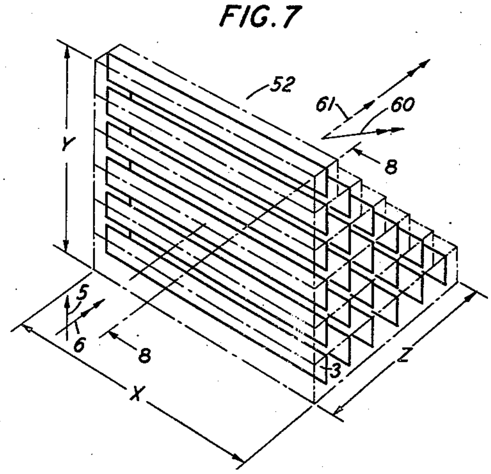


FIG. 9

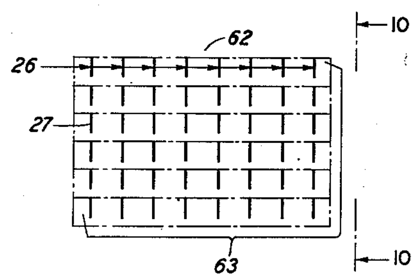


FIG. 8

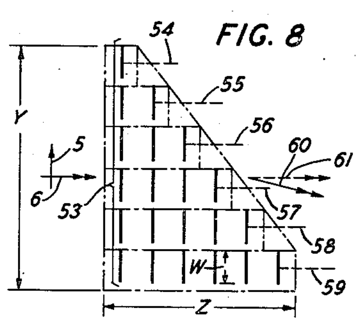
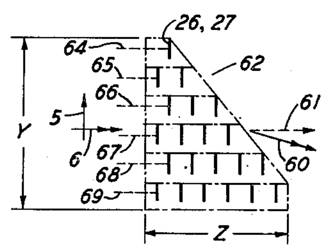


FIG. 10



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METALLIC STRUCTURE AND DELAYING UNIPOLARIZED WAVES

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FIG. 11

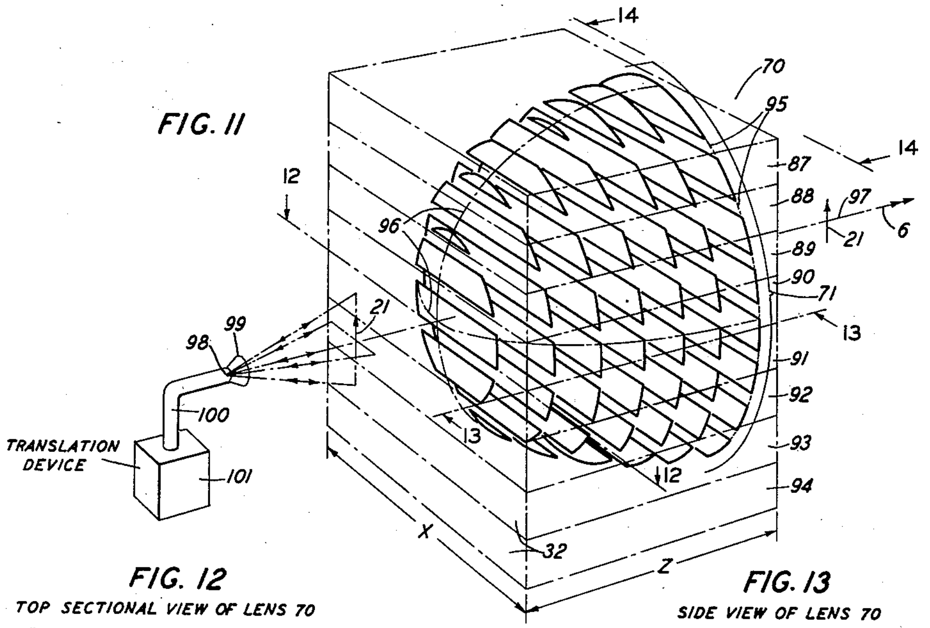


FIG. 12

TOP SECTIONAL VIEW OF LENS 70

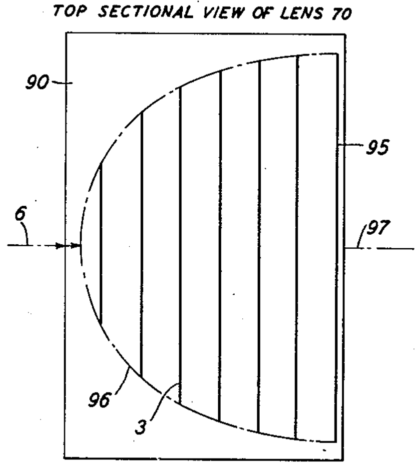


FIG. 13

SIDE VIEW OF LENS 70

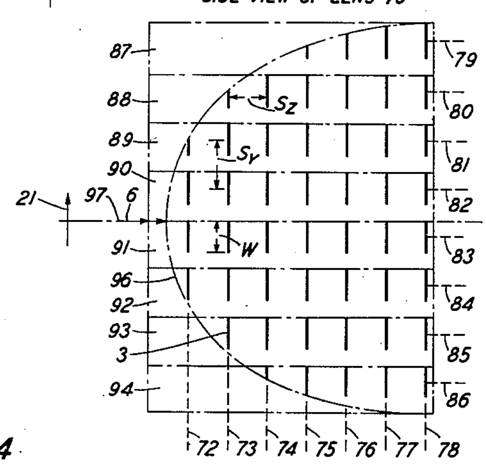
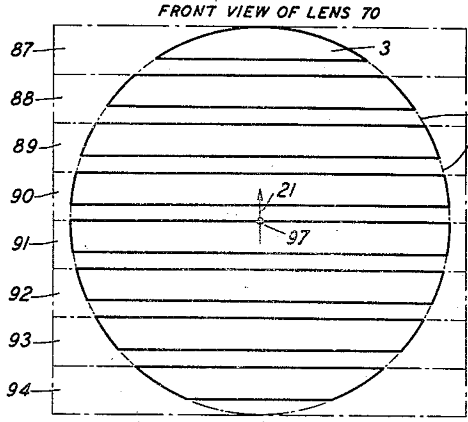


FIG. 14

FRONT VIEW OF LENS 70



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METALLIC STRUCTURE AND DELAYING UNIPOLARIZED WAVES

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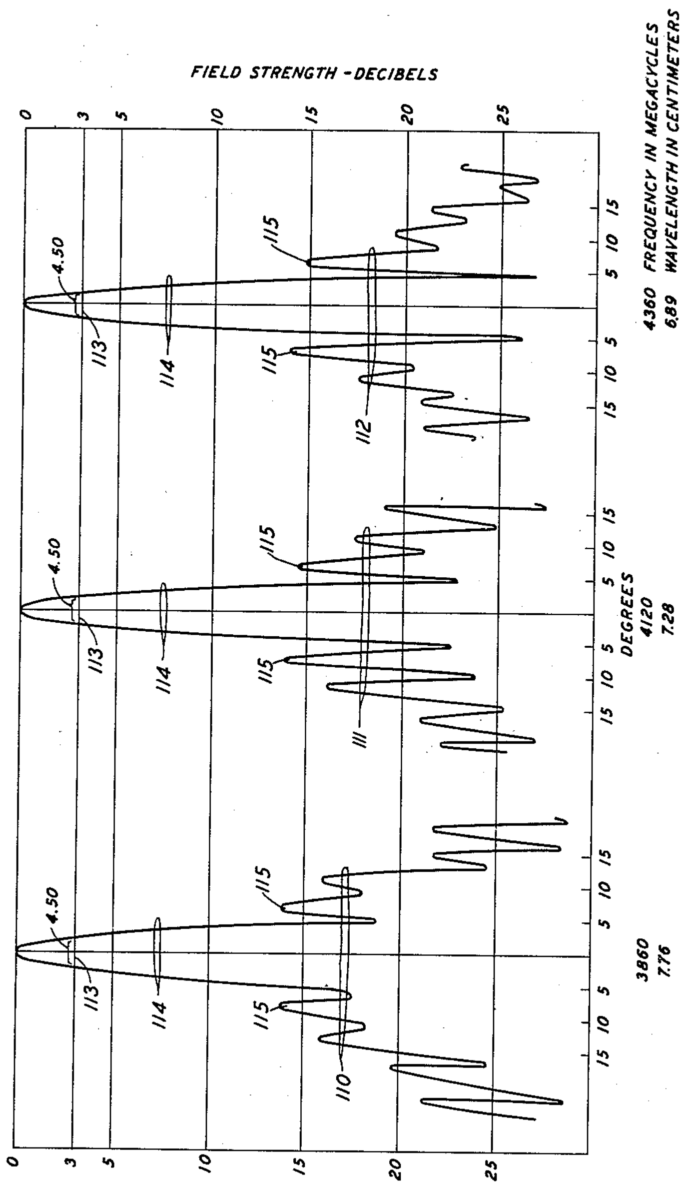
FIG. 17

FREQUENCY-DIRECTIVE CURVES OF SYSTEM OF FIG. 11
OVER 12 PER CENT BAND



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METALLIC STRUCTURE AND DELAYING UNIPOLARIZED WAVES

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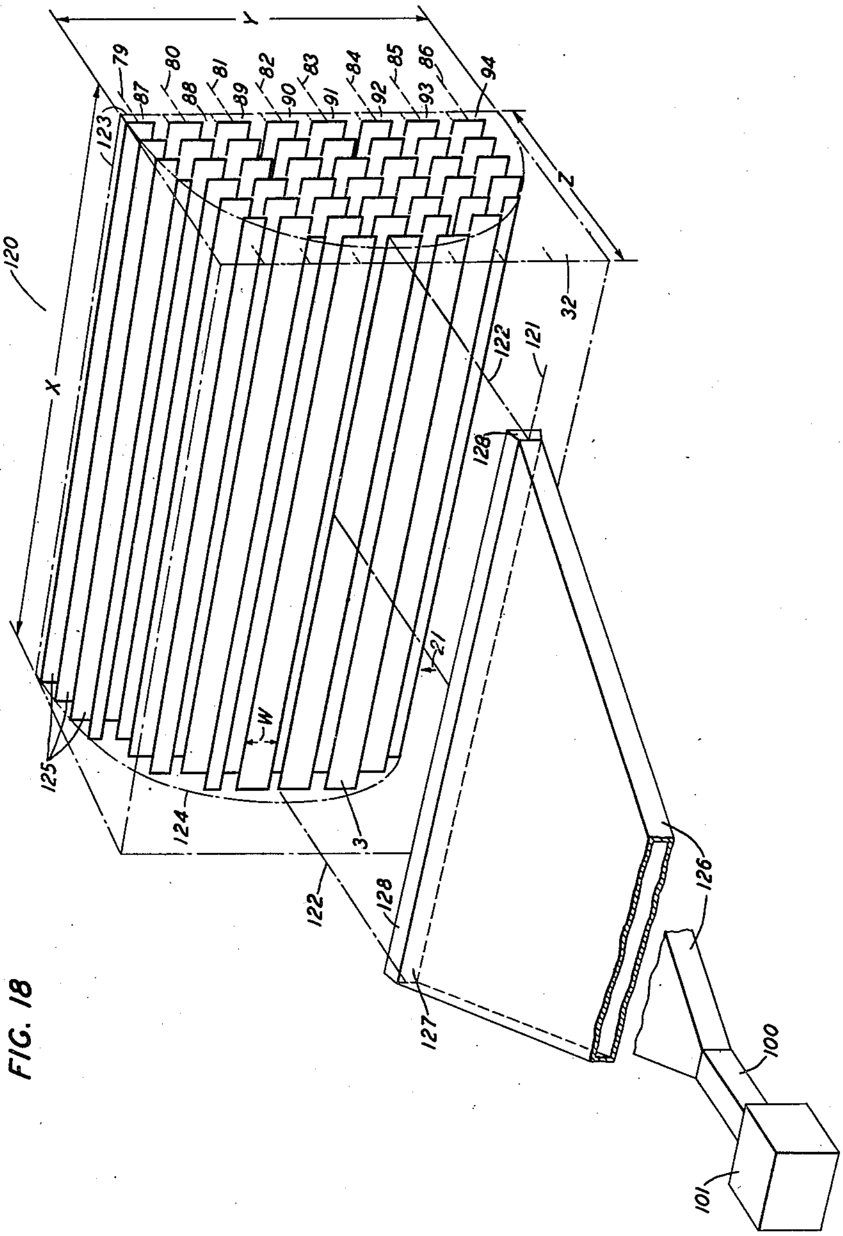

FIG. 18

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METALLIC STRUCTURE AND DELAYING UNIPOLARIZED WAVES

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FIG. 20

FRONT VIEW OF LENS 130

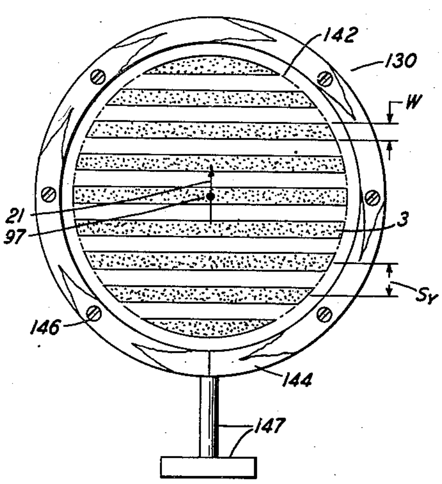


FIG. 22

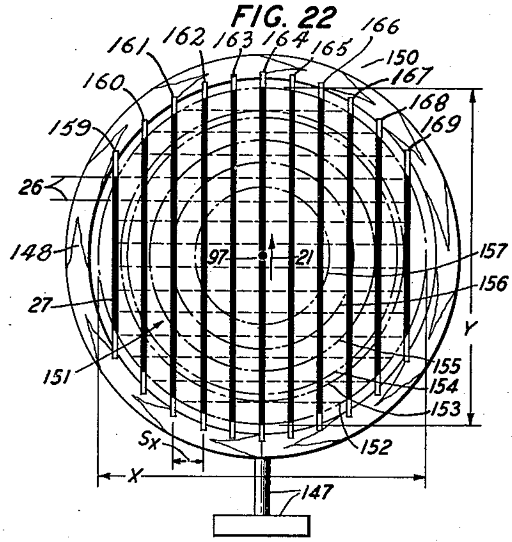


FIG. 19

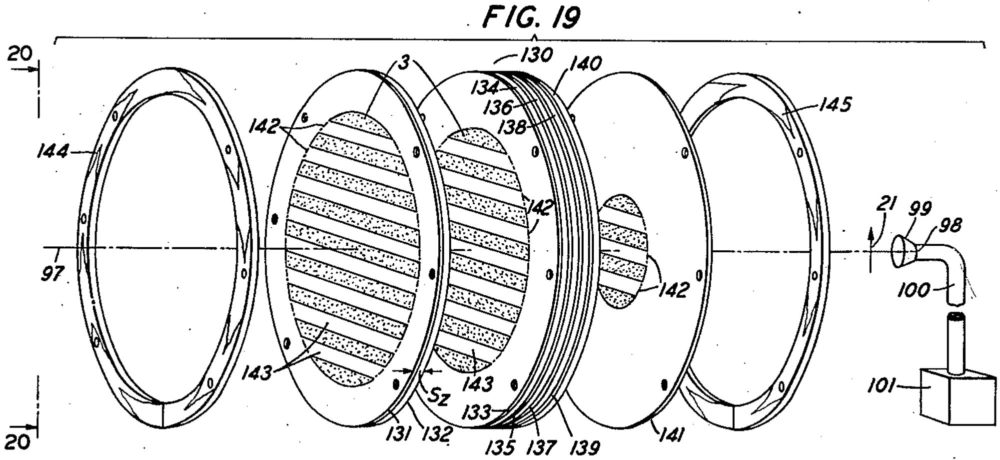


FIG. 23

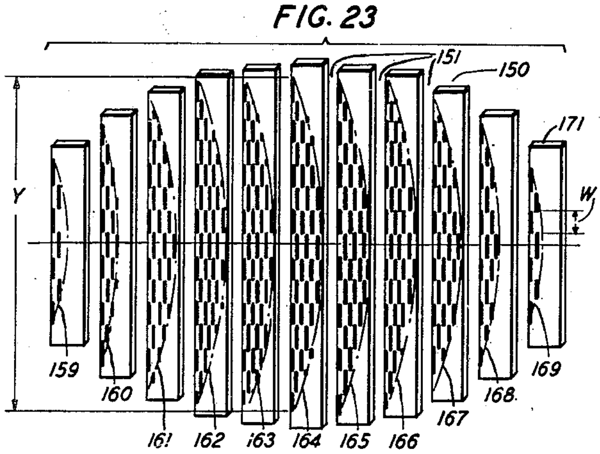
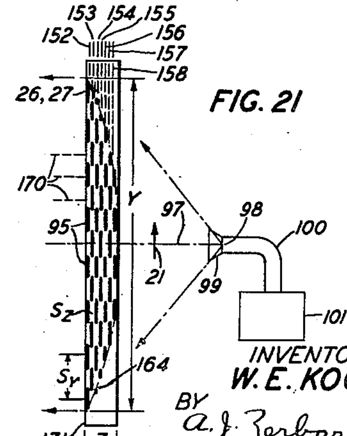


FIG. 21



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METALLIC STRUCTURE AND DELAYING UNIPOLARIZED WAVES

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FIG. 24

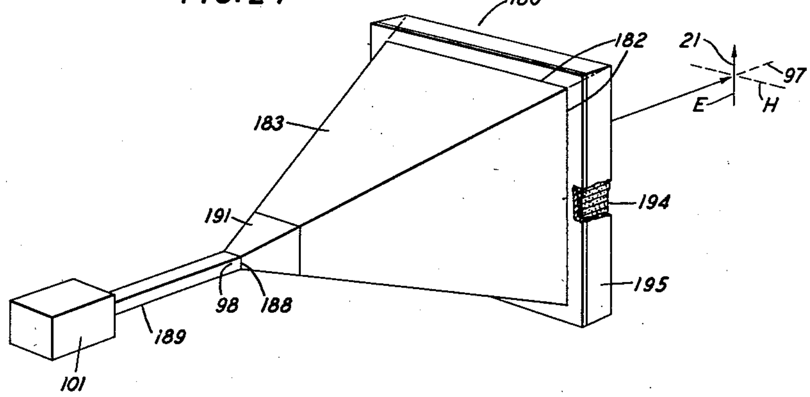

FIG. 26

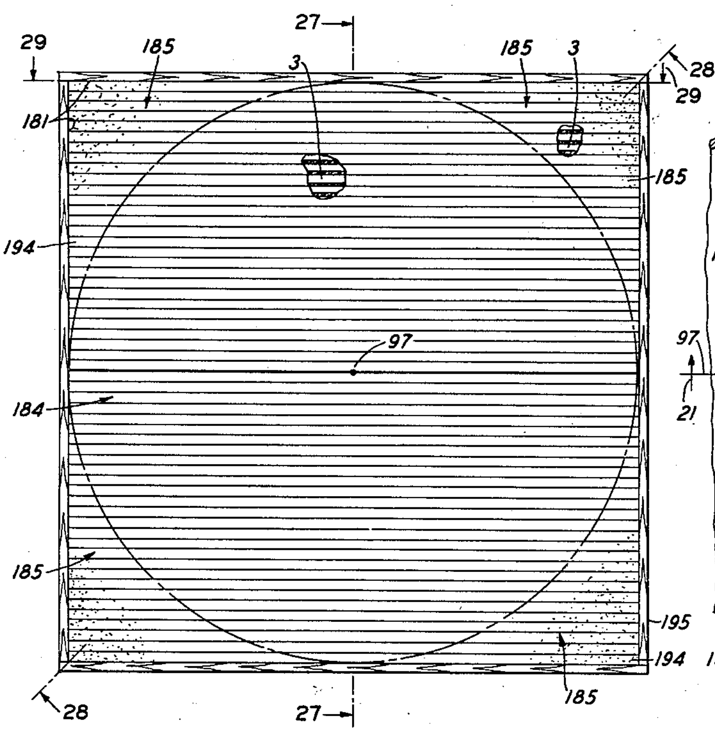

FIG. 27

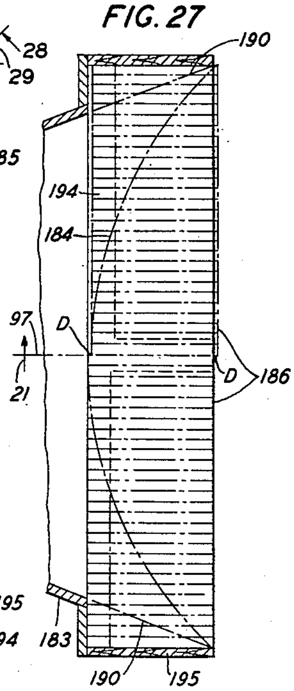

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FIG. 25

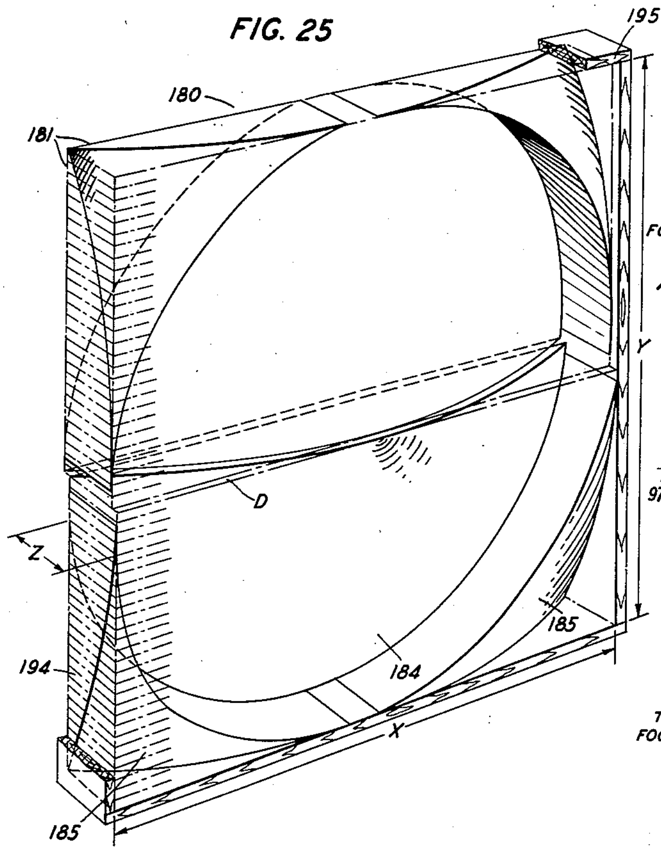


FIG. 28

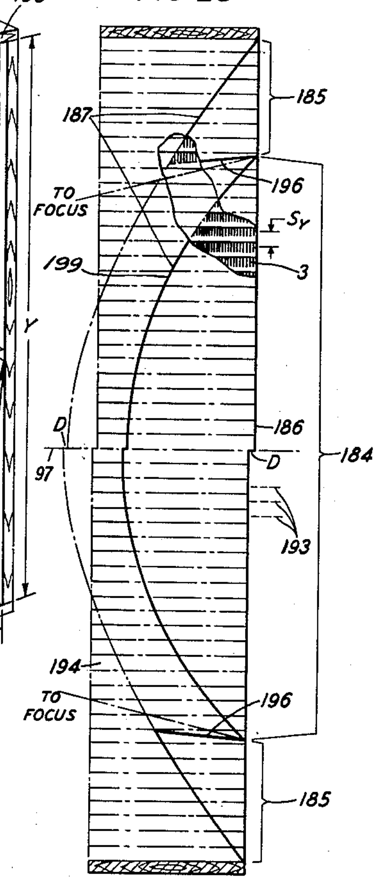


FIG. 29

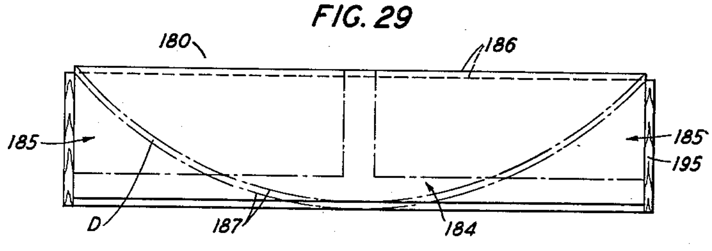
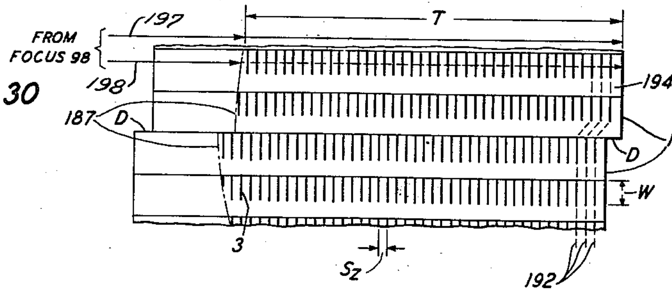


FIG. 30



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METALLIC STRUCTURE AND DELAYING UNIPOLARIZED WAVES

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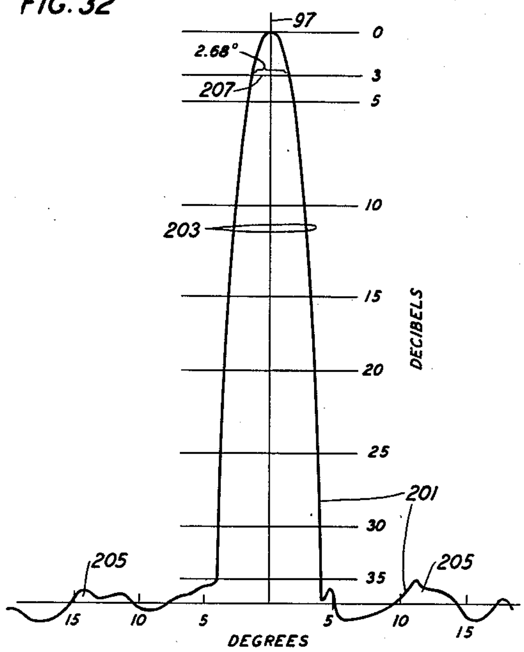
DIRECTIVE PATTERN OF LENS-HORN 180, 183

FIG. 32



DIRECTIVE PATTERN OF LENS 180

FIG. 31

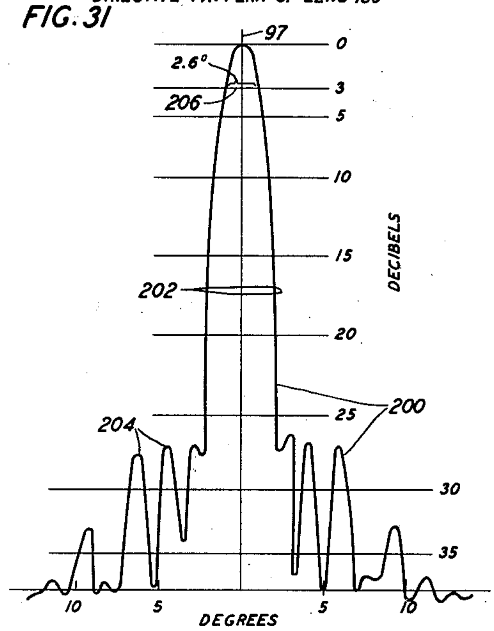


FIG. 33

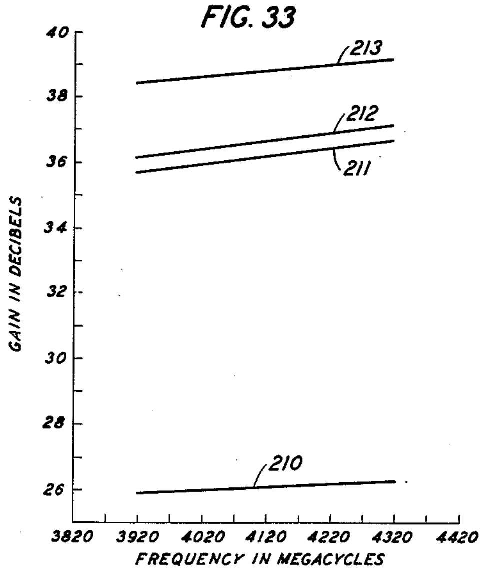


FIG. 34

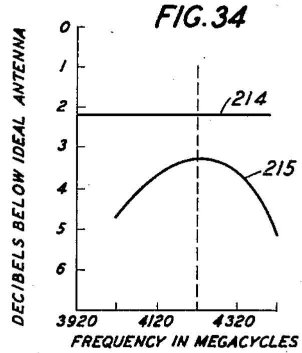
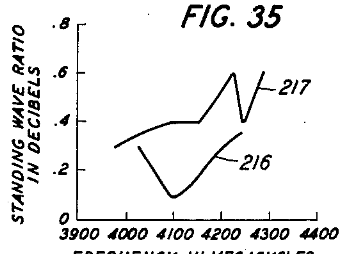


FIG. 35



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Patented Dec. 4, 1951

2,577,619

UNITED STATES PATENT OFFICE

2,577,619

METALLIC STRUCTURE FOR DELAYING UNIPOLARIZED WAVES

Winston E. Kock, Middletown, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application May 16, 1947, Serial No. 748,448

11 Claims. (Cl. 250—33.63)

1

This invention relates to passive devices for changing the phase velocity of electromagnetic waves and, in particular, to radio refractors designed for use in directive and non-directive antenna systems.

As is known, metallic-dielectric structures comprising iron wires immersed in a solid dielectric substance have been suggested for generating short (10–185 meters) radio waves, and an end-on array of passive wires or directors spaced in the air dielectric medium has been proposed for directively propagating short radio waves. Also solid dielectric delay, or so-called velocity-decrease, refractors of the focussing and non-focussing types, have been proposed for changing the wave propagation direction. In addition, "fast" or metallic-advance, or so-called velocity-increase, wave changers for altering the wave polarization, lenses for focussing the waves and prisms for bending the propagation direction, have been utilized in very short wave (1–10 meters), ultra-short wave (10–100 centimeters) and super-short wave or microwave, (1–10 centimeters) antenna systems. Thus, Patent 706,739, granted to R. A. Fessenden on August 12, 1902, discloses a metallic-dielectric short wave generator; Figs. 1 and 4 of Patent 1,860,123 granted to H. Yagi on May 24, 1932, discloses an end-on array of director wires; Fig. 21 of Patent 2,283,935, granted to A. P. King on May 26, 1942, illustrates a horn antenna having a solid dielectric isotropic delay lens in its mouth aperture, and my copending applications Serial Nos. 642,722 and 642,723, both filed on January 22, 1946, disclose metallic-advance wave changers, lenses and prisms. The refractive index of the isotropic delay lens mentioned above is, of course, greater than unity, whereas the refractive index of the metallic-advance lens is smaller than unity.

In general, the above-mentioned solid dielectric delay lens has a broad bandwidth inasmuch as it is ordinarily utilized for frequency bands in which the variation with frequency of the dielectric constant, and hence of the refractive index, is zero or negligible. On the other hand, the end-on array mentioned above is frequency sensitive since the director wires are only slightly shorter than one-half the operating wavelength. Also, the metallic-advance lens has a fairly narrow band width, inasmuch as the refractive index is dependent primarily on the plate spacing, that is, the channel width as measured in wavelengths, and the plates spacing varies rapidly with frequency.

The metallic-advance lens has, however, distinct advantages, not found in the metallic-dielectric wave generator or in the solid dielectric lens. Thus, the prior art metallic-dielectric and

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solid dielectric structures are relatively heavy and cumbersome, and the waves passing through these structures are attenuated, the total energy loss being considerable. On the contrary, the fast or metallic-advance lenses described above are lightweight and substantially lossless. Again, the directivity gain of the solid dielectric delay lens is relatively low, whereas the directivity gain of the metallic-advance lens is comparatively high. Accordingly, it now appears desirable to obtain metallic wave changers including polarizers, prisms and lenses, which possess the attributes, but are devoid of the disadvantages, inherent in the above-mentioned prior art structures. In particular, it now appears desirable to secure a lossless, unipolarized, or an isotropic broad-band, lightweight metallic lens.

It is one object of this invention to retard very short, ultra-short and super-short radio waves in an efficient and substantially lossless manner.

It is another object of this invention to change a characteristic of an electromagnetic wave, such as the direction or type of polarization, the propagation direction, or the phase velocity, in a more efficient and satisfactory manner than heretofore accomplished.

It is another object of this invention to refract, with or without focussing and with only negligible loss, electromagnetic waves included in an exceedingly large band of wavelengths.

It is another object of this invention to eliminate, in a wave changer such as a lens or prism, reflection loss in a simpler and more satisfactory manner than heretofore accomplished.

It is another object of this invention to secure, in a unipolarized metallic lens, a high gain, broad-band characteristic.

It is still another object of this invention to obtain, in a metallic refractor, an effective dielectric constant greater than unity and substantially independent of the permeability of the metallic elements.

It is another object of this invention to obtain a broad band unipolarized refractor which, as compared to broad band unipolarized structures heretofore utilized, is lighter, simpler and less expensive.

In accordance with the invention a unipolarized metallic-delay structure comprises a dielectric medium, such as air or polystyrene foam, and an array of flat linear conductive members extending parallel to the magnetic polarization, that is, the H vector, of an incoming electromagnetic wave and hence parallel to the X dimension of the structure. The members are spaced in the medium along the perpendicular Y and Z directions which are parallel, respectively, to the vertical electric (E) vector and the horizontal propagation direction of the wave.

The linear members are of the "strip" type, that is, each member has a continuous or integral surface and is formed, for example, of sheet metal having a thickness of 0.005 inch. The flat sides of the strips are parallel to the E vector or height Y. The width W or height, that is, the dimension measured parallel to the E vector, of each strip, and the center-to-center spacing of the strips along the Y and Z dimensions are considerably smaller than one-half of the minimum wavelength in the operating band, the width being preferably a quarter of said wavelength or less.

The dielectric constant of the medium is negligible and the effective dielectric constant of the conductive array, for the assumed E vector, is greater than unity. As explained herein, the effective dielectric constant is a function of the electric polarizability of a typical member and the number of members dispersed in a unit area, taken in the YZ plane of the array. Hence the refractive index of the array is greater than unity and the aray or structure functions to decrease the phase velocity of a wave or wave component passing through the array and having the assumed vertical E polarization. A horizontal E vector is completely reflected by the horizontal strips and the cut-off orifices between the adjacent strips. Accordingly, only waves having the assumed E polarization are delayed and, as indicated above, the structure is unipolarized. Also, in accordance with the invention, the loss resulting from the reflection, if any, of the vertical E vector at the back and front faces of the array, are substantially eliminated by displacing the lower half of the array, relative to the upper half, a quarter wavelength along the propagation direction. The contours of the front and back faces of the array, or of the structure comprising the array and the medium, are such that the array or structure constitutes a refractor of the focussing or non-fucussing type. In one embodiment, the structure is shaped so as to constitute a plano-hyperbolic lens. In another embodiment the structure has the shape of a prism.

The linear horizontal members mentioned above may be of the grid type, instead of the strip type, that is, each member may comprise vertical elements or wires spaced horizontally less than a half wavelength and having length dimensions equal to the width dimension W of the member. Assuming grid members are utilized, the vertical E vectors are propagated through the array, as explained above, since the grid member functions, in effect, as a strip member for this orientation of the E polarization; and the phase velocity is decreased. Horizontal E vectors are, however, not reflected but pass through the horizontal grid members, and through the openings between adjacent grid members, without change in phase velocity. As in the strip array or structure, the grid array or structure is shaped, in one embodiment, so as to constitute a plano-convex lens and, in another embodiment, so as to constitute a prism. In still another embodiment, the array has a constant critical depth or Z-dimension and, assuming the E vector is oblique, the array constitutes a polarization circularizer or a polarization quadrature rotator.

It may be pointed out that the grid array described above should be sharply distinguished from the grid structures illustrated by Fig. 3 of my copending application for "Transmission Systems," Serial No. 748,447, filed on May 16, 1947, concurrently with the present application. In the structure of my copending application the spacing between the vertical wires or elements in each horizontal grid member, while less than one wavelength, may be greater than a half wavelength, whereby the vertical E vector is not reflected by the horizontal grid members and the vector components are not forced to pass, in each vertical panel, between the adjacent horizontal grid members. It may also be added that the thin linear strip or grid members do not, as in the case of the disk elements disclosed in my copending application just mentioned, perturb the magnetic or H field of the incoming wave and, accordingly, the effective dielectric constant of the array is not detrimentally affected by the H vectors.

The invention will be more fully understood from a perusal of the following specification, taken in conjunction with the drawing on which like reference characters denote elements of similar function and on which:

Fig. 1 is a perspective view of a phase velocity changer constructed in accordance with the invention and comprising linear strip members, and Fig. 2 is a diagram used in explaining Fig. 1;

Fig. 3 is a perspective view of another phase velocity change reconstructed in accordance with the invention and comprising linear grid members, and Fig. 4 is a diagram used in explaining Fig. 3;

Fig. 5 is a perspective view of a polarization rotator or circular polarizer constructed in accordance with the invention and comprising several tiers and Fig. 6 is a partial perspective view of one of the tiers included in the structure of Fig. 5;

Figs. 7 and 8 are, respectively, perspective and end views of a strip prism constructed in accordance with the invention;

Figs. 9 and 10 are, respectively, front and end views of a grid prism constructed in accordance with the invention;

Fig. 11 is a perspective view of a point-beam antenna system comprising a plano-convex, circularly symmetrical, strip lens constructed in accordance with the invention, and Figs. 12, 13 and 14, are respectively top sectional, side and front views of the lens included in the system of Fig. 11;

Figs. 15 and 16 are diagrams used for explaining the shape or contour of the lens of Fig. 11;

Fig. 17 is a set of curves illustrating the directive band width characteristics of the system of Fig. 11;

Fig. 18 is a perspective view of a fan-beam antenna system comprising a plano-convex, cylindrically symmetrical, strip lens constructed in accordance with the invention;

Fig. 19 is a perspective view of a point-beam antenna system comprising a different plano-convex, circularly symmetrical, strip lens constructed in accordance with the invention, and Fig. 20 is a front or back view of the lens of Fig. 19;

Fig. 21 is a sectional side view of a point-beam antenna system comprising a plano-convex, circularly symmetrical, grid lens constructed in accordance with the invention, and Figs. 22 and 23 are, respectively, front and exploded perspective views of the lens of Fig. 21;

Fig. 24 is a perspective view of a point-beam antenna system comprising a pyramidal horn equipped with a stepped, plano-convex, circularly symmetrical strip lens constructed in accordance with the invention; and Figs. 25, 26, 27, 28, 29 and 30 are, respectively, perspective, front, vertical sectional, diagonal sectional, top, and partial end views of the stepped lens included in the system of Fig. 24;

Figs. 31 and 32 are directive patterns of the lens of Fig. 24 taken, respectively, with the horn sides or shields removed and with the horn sides in position;

Figs. 33 and 34 illustrate the directivity bandwidth characteristic, and Fig. 35 illustrates the reflection-frequency characteristic, of the system of Fig. 24.

Referring to Fig. 1 reference numeral 1 denotes a wave delay structure comprising a dielectric medium 2, such as air, and nine linear conductive strip members 3, as for example, sheet-metal strips, spaced along the Y and Z dimensions of the assumed volume X, Y, Z of the medium. The nine strip members 3 form an array or metallic structure 4, or so-called artificial dielectric material which, as will be more fully explained hereinafter, functions to delay the phase velocity of electromagnetic waves. Numerals 5 and 6 denote arrows representing, respectively, the electric polarization E and the direction of propagation of the incoming wave; and numerals 7 and 8 designate, respectively, the plane of the incoming wave front and the vertical plane of wave propagation. The width W, parallel to the E vector 5, of each strip 9 is made small relative to one-half the shortest operating wavelength, for example, one quarter wavelength, in order to avoid resonant effects which may occur when the width is in the vicinity of one-half wavelength. The center-to-center spacings S_y and S_z along the Y and Z dimensions are each less than one wavelength and preferably less than a half wavelength. As will be explained, the spacings are dependent upon the selected number N of strips per square unit area, observed looking at the end of the array, that is, the number per square unit area, of strips intersecting the YZ plane of the array. The spacings between adjacent strips, which in effect constitute electric dipoles, should be greater than the so-called breakdown value or, in other words, sufficiently great to prevent short-circuiting of the strips. The nine strips are arranged in three vertical panels 9, 10, 11 of three strips each or, considered differently, they are arranged in three horizontal tiers 12, 13 and 14. As is apparent from the drawing, the corresponding strips in the three panels are horizontally aligned. Numerals 15 and 16 denote respectively the front and back faces of the structure 1.

Assuming an electric field E having a polarization 5 and a propagation direction 6 is impressed on the array 4, the field produces a redistribution of the charges on the conductor strips 3. Each strip in effect comprises an infinite number of vertical linear elements 17 of infinitesimal thickness, and the impressed field causes these elements to act like small electric dipoles. Each of these dipoles possesses a certain electric dipole moment which is related to the impressed electric vector 5 and the electric polarizability of the element, and hence of the strip, by the equation

$$\overline{M}=\alpha\overline{E} \tag{1}$$

where

$\overline{M}$ is the electric dipole moment

α is the polarizability of the individual strip 3 and

$\overline{E}$ is the impressed electric vector.

Assuming there are N strips 3 per unit area, taken in the YZ plane, of the dielectric medium 2

$$\overline{P}=N\alpha\overline{E} \tag{2}$$

where

$\overline{P}$ is the total polarization of all the strips 3, that is, of the array 4 which is immersed in the dielectric medium 2. But, as explained in my copending concurrently filed application, Serial No. 748,447,

$$n=\frac{v_0}{v}=\frac{\lambda_0}{\lambda} \tag{3}$$

$$n^2=\frac{\epsilon}{\epsilon_0}=\epsilon_r \tag{4}$$

and

$$n^2=1+\frac{N\alpha}{\epsilon_0} \tag{5}$$

where,

n is the refractive index of the array 4;
ϵ is the effective dielectric constant of the array 4;
ϵ_0 is the dielectric constant of free space;
ϵ_r is the relative dielectric constant;
v is the phase velocity of the waves in the array 4;
v_0 is the phase velocity of the waves in free space;
λ is the wavelength as measured in the array 4, and
λ_0 is the wavelength in free space.

Hence, if the electric polarizability, α_m, of the typical strip member 3 is known, the refractive index n of the array 4, may be ascertained. Since the dielectric constant of the air medium 2 is unity, and therefore, negligible, the refractive index of the structure 1 is the same substantially, as the refractive index of the array 4. As shown below, the polarizability of the strip is directly proportional to the square of the width, W, of the strip. Also, as shown below, the electric polarizability of the strips 3 is positive, so that from Equation 5, we have

$$n>1 \tag{6}$$

that is, the refractive index of the array 4, or of the structure 1, is greater than unity. Hence v_0 and λ_0 are, respectively greater than v and λ; and the array 1 constitutes a metallic-delay wave changer for decreasing the phase velocity of waves having the E polarization 5.

Considered from a different viewpoint, the strips, or more accurately the infinitesimal segments 17, may be regarded as capacitative conductors which load free space. Analogously, shunt capacitors along a transmission line function to reduce the wave velocity. To continue the analogue, in the case of a charged parallel plate air condenser, the capacity may be increased by inserting between the plates either solid dielectric material or insulated conducting objects, provided the objects or elements each have an appreciable length in the direction of the electrostatic lines of force, that is, in a direction perpendicular to the plates. Assuming solid dielectric material is inserted, the increase in capacity is caused by the shift, produced by the applied field, of the oppositely charged particles comprising the molecules of the solid material. Assuming spaced conductive strips 3 are inserted between the plates, the width dimension W being perpendicular to the plates, the strips 3 or segments 17 cause a rearrangement of the lines of force, and a consequent increase in their number, similar to the rearrangement caused by the shift, mentioned above, of the oppositely charged particles. Hence, the strips **3** or segments **17**, Fig. 1, may be considered as segments of individual condensers or as objects which, under the action of the applied field, function as electric dipoles and produce a dielectric polarization comparable to that resulting from the rearrangement of the charged particles comprising a nonpolar dielectric. Both the polarizability theory and the capacity loading theory explain satisfactorily the delay characteristic of the metallic wave change of Fig. 1, and of the metallic delay prisms and lenses.

The electric polarizability of the strip **3** may be determined from Equation 15 on page 97 of the textbook "Static and Dynamic Electricity" by Smythe, for the torque of an elliptic dielectric cylinder. Thus,

$$\alpha_m = \frac{\pi \epsilon_0 W^2}{4} \qquad (7)$$

where

α_m is the electric polarizability of the strip **3**;
ϵ_0 is the dielectric constant of free space, as before, and
W is the strip width.

Hence, substituting the value of α_m as given in Equation 7 for α in Equation 5 we have for the refractive index n of the array **4**,

$$n = \sqrt{1 + \pi \frac{W^2 N}{4}} \qquad (8)$$

where, as above, N is the number of strips per square unit area taken in the YZ plane.

It is apparent from Equations 7 and 8 that the electric polarizability α_m and the refractive index n are each directly proportional to the square of the width W of the strip. The refractive index n is also directly proportional to the number N of strips per square unit area in the YZ plane. The number N is dependent on the center-to-center vertical spacing S_y and the center-to-center horizontal spacing S_z of the strips; and these spacings may or may not be equal, as is desired. With the desired index n and hence the desired phase velocity change $v_0 - v$, selected, and with W given, the number N of strips, and hence the spacings S_y and S_z, may be determined. Conversely, with W and N selected, the theoretical value of the refractive index as, for example, 1.36, may be ascertained.

Equations 5 and 8 are based on the assumptions that the strip width W is small relative to a half wavelength of the wave and that the spacings S_y and S_z between strips are sufficiently large to avoid appreciable mutual coupling. For optimum operation W should be less than a quarter wavelength.

Thus far only the electric (E) field of the incoming wave has been considered. The magnetic (H) field of the way may be disregarded, that is, the relative permeability μ_r of the array may be assumed to be unity, the same as air, inasmuch as the strips **3** have a negligible thickness or Z dimension. More specifically, by virtue of the negligible strip thickness eddy currents are not produced on the strips by the attenuated H field and, accordingly, the H field is not perturbed. Since the H field is not perturbed it does not affect the refractive index. In this respect the strips correspond to the disk elements disclosed in my copending, concurrently filed, application, Serial No. 748,447, rather than to the spherical elements disclosed therein.

If, instead of air, a substance, such as hard rubber, having a dielectric constant ϵ_m substantially different from unit is utilized in place of the air medium **2**, and as a filler, the effective dielectric constant ϵ_c of the modified structure **1** may be determined from the following equation

$$\log \epsilon_c = k_s \log \epsilon + k_m \log \epsilon_m \qquad (9)$$

where k_s and k_m are the volume proportions, in per cent, occupied by the conductive structure and the medium, respectively, in a unit volume of the structure. By substituting for ϵ, Equation 4, the value of ϵ_c, as determined from Equation 9, the refractive index of the modified structure may be ascertained.

In operation, Figs. 1 and 2, waves having an E polarization **5** and a propagation direction **6** pass through the structure **1** and, as explained above, the phase velocity of the waves is decreased from v_0 to v. Since the strip or dimension (W), in a direction parallel to the electric vector, is small relative to a half wavelength, the E vector is not short-circuited and reflection of the E vector **5** is negligible. According to one plausible theory, the vertically spaced horizontal strips **3** in each vertical panel in effect divide the E vector into colinear components and force these components to pass into the openings **18** between the adjacent strips. The horizontal component, if any, of the electric vector of the incoming wave is reflected in part by the strips **3** and in part by the cut-off dielectric guide spacings a between the adjacent strips, the spacing a or width of the openings **18** being less than a half wavelength. Thus, assuming the wave has a tilted or oblique E vector **19**, Fig. 1, the horizontal E component **20** is reflected by the strips **3** and the openings **18**, as shown in Fig. 2 by the dotted arrows **22**, and the vertical E component **21** passes through the array and is retarded, as explained above and as shown in Fig. 2 by the dot-dash arrows **23**. Accordingly, the array **4** or structure **1**, is unipolarized.

By way of comparison, it may be pointed out that the quasi-isotropic structure, disclosed in my copending concurrently filed application, Serial No. 748,447, and comprising painted disks, may be rendered unipolarized by reducing, in each vertical panel, the horizontal spacing S_x between disks to zero and, in this manner, securing strips of contiguous disks which simulate or resemble the rectangular metallic strips **3** of Fig. 1.

Referring to Fig. 3, reference numeral **24** denotes a wave changer comprising an air dielectric medium **2** and a metallic array **25** immersed therein. The array **25** is the same as the array **4**, Fig. 1, except that the nine linear conductive members **26** are of the grid, instead of the strip, type. Each horizontal grid comprises a plurality of vertical elements **27**, wires or rods, spaced apart a distance S_r smaller than one-half the minimum operating wavelength and each having a length equal to the width W, of the member. As in the array **4** of Fig. 1 the center-to-center spacings S_y and S_z, along the Y and Z dimensions, of the members **26** are each less than the minimum wavelength and preferably less than one-half of the aforesaid wavelength. Also, as in the structure **4** of Fig. 1, the nine linear members **26** are arranged in three vertical panels **9**, **10**, **11** of three grids each or, considered differently, they are arranged in three horizontal tiers **12**, **13** and **14**. The corresponding strips in the three panels are horizontally aligned. The electric polarizability am of the typical grid member 26, Fig. 3, is the same as that of the typical strip member 3, Fig. 1. With N, and hence S_y and S_z selected, and W given, the refractive index n, which is greater than unity of the array 25 or changer 24 may be determined. Assuming the changer is to be used as a polarization circularizer, the Z dimension or thickness of the changer, as measured in wavelengths in the array is one-quarter wavelength, or an odd multiple thereof, larger than the same thickness Z, as measured in free space. If it is to be utilized as a 90-degree polarization rotator, the thickness Z, as measured in wavelengths in the array is one-half wavelength, or a multiple thereof, greater than the same thickness Z as measured in air.

In operation, Fig. 3, assuming an oblique E vector 19 titled at 45 degrees relative to the rods 27 and having the proper wavelength is incoming to the changer 24 along the path 6, and that the wave changer is employed as a polarization circularizer, the horizontal E component 20 of the vector 19 passes through the grids 26, since this component is perpendicular to the rods, as shown by the arrows 29, Fig. 4. The phase velocity of the horizontal component 20 is not decreased by the array 25, but the phase velocity of the vertical vector component 21 is delayed 90 degrees relative to the horizontal component. Since the spacing S_r between the adjacent rods 27 is each grid 26 is smaller than a half wavelength, the vertical E component 21 of wave 19 does not pass between the rods and accordingly, for this component, each grid member 26 functions like a strip member. As shown by the arrows 28, Fig. 4, the vertical component is propagated through the orifices 18 between the grids 26 in each panel and little, if any, reflection of this component occurs. Hence, upon emerging from the changer, the two components 20 and 21 are in time quadrature and, since they are in space quadrature, the emergent wave is circularly polarized.

Assuming now that the wave changer 24 is utilized as a polarization rotator, the horizontal component 20 is retarded 180 degrees relative to the vertical component 21, and the polarization of the resultant outgoing vector 30 is perpendicular to the polarization of the incoming vector 19. In other words, the polarization of vector 19 is rotated 90 degrees. It may be observed here that, since the circularizer and rotator just described are of the velocity-decrease type, they are distinguishable from the velocity-increase circularizer and rotator disclosed in my copending application Serial No. 642,722, filed January 22, 1946.

Referring to Figs. 5 and 6, the wave changer 31 is basically the same as the changer 21 except that the dielectric medium 32 is polystyrene foam instead of air. The polystyrene foam medium has a dielectric constant of 1.014 and a refractive index of 1.007 and, in this respect, is substantially the same as the air medium which has a dielectric constant equal to unity and a refractive index equal to unity. More specifically, the wave changer 31 comprises an array 25 of 960 metallic rods arranged in ten vertical panels 33–42 each comprising eight horizontal rows of rods 27 spaced less than a half wavelength apart. Stated differently, the 960 rods are arranged in eight tiers 43 to 50, each comprising ten horizontal linear grid members 26 and the members 26 each comprising twelve vertical rods 27. As shown in Fig. 6, the ten grid members of each tier are mounted or embedded in a horizontal polystyrene foam slab 51. The eight slabs 51 for the eight tiers are vertically stacked so that the grid members 26 are spaced along the Y and Z dimension of the structure. The operation of the wave changer 31 as a polarization circularizer or as a polarization rotator is the same as that of the wave changer 21, Fig. 3.

Referring to Figs. 7 and 8, reference numeral 52 denotes a metallic delay prism comprising an array 53 immersed in a polystyrene foam medium 32. The array 53 comprises 21 conductive strip members 3 arranged in six horizontal tiers 54 to 59 of 1, 2, 3, 4, 5 and 6 strips, respectively. The six tiers are mounted in individual polystyrene foam slabs 51, each strip being fitted into a linear slot in the foam; and the Z dimension of the slabs are stepped, as illustrated, so as to form the prism. The corresponding strips in each tier are horizontally aligned. As in the structure of Fig. 1, the electric polarizability and the refractive index of the prism 52 may be determined from Equations 7 and 8, respectively.

In operation, assuming the wave incoming to the prism travels along path 6 and has an E vector parallel to the width W of the strip, the wave front portion passing through the thicker or bottom section of the prism is retarded a greater amount than the wave front portion passing through the thinner or upper section of the prism. Hence the wave direction 6 is bent or refracted as shown by arrow 60, the amount of refraction being dependent upon the refractive index n of the prism. In each of Figs. 7 and 8 the dotted arrow 61 denotes the outgoing propagation direction which the waves would have if the wave direction were not bent by the prism. Since only waves having an E vector, or an E vector component, parallel to the width W of the strips are retarded, the prism is a unipolarized delay structure.

Referring to Figs. 9 and 10, the metallic delay prism 62 comprises an array 63 which is immersed in the polystyrene foam medium 32. The array 63 comprises, as in Fig. 8, twenty-one conductive grid members 27 arranged in six horizontal tiers 64 to 69 of 1, 2, 3, 4, 5 and 6 grids, respectively, the six tiers being mounted in individual foam slabs 51. The grids in adjacent tiers are staggered so that, as compared to the array 53, Fig. 8, the array 63 contains a large number N of metallic members 26 per unit area in the YZ plane. Accordingly, assuming the polarizability of the grid members 26, Fig. 10, is the same as that of the strip members 3, Fig. 3, the refractive index of the array 62, Fig. 10, is greater than that of the array 53, Fig. 8. The staggered arrangement permits a more compact construction. As in the prism 52 of Figs. 7 and 8, and as shown by arrow 60, in operation, the prism 62 is unipolarized and functions to refract waves having an E vector 5 and a propagation direction 6.

Referring to Figs. 11, 12, 13 and 14, reference numeral 70 denotes a unipolarized, circularly symmetrical, metallic delay lens comprising an array 71 of forty-nine conductive strip members 3 spaced apart a distance S_y along the Y dimension, and a distance S_z along the Z dimension, of the polystyrene foam medium 32. The forty-nine strips 3 are arranged in seven vertical panels 72 to 78 or, stated differently, in eight horizontal tiers 79 to 86. The foam medium 32 comprises eight vertically stacked slabs 87 to 94 which contain vertical slots for retaining the strips 3 and support, respectively, the eight tiers 79 to 86. Numerals 95, 96, 97 and 98 denote, respectively, the front plane face, the back convex face, the optical axis and the point focus of the lens 70. As shown on the drawing, the lengths of the slots and the strips 3, and the depths of certain outer slots and the widths of the corresponding outer strips, are selected so as to conform to the convex contour of the back face 96 of the lens. Accordingly, while the number N of strips per unit area of the YZ section is constant throughout the array 71, the array includes fractional, as well as whole strips. Numeral 99 denotes a conical, point-type horn having its throat orifice positioned at the focal point 98 and connected by the dielectric guide 100 to a translation device 101.

As in the polarization circularizer, polarization rotator and prisms heretofore described, with W and N and hence S_y and S_z, selected, the polarizability α and the refractive index n, greater than unity, may be ascertained. Conversely, with n and W selected the value of N and hence the values S_y and S_z, may be determied.

Referring to Fig. 15, the equation for the contour of the convex face 96, which faces towards the focus 98 and the horn 99, will now be determined. In Fig. 15, the reference letter A denotes the phase length of the path traversed by a wavelet or ray emitted at the focus 98 and propagated through the thick portion of the lens and along the axis 97 of the flat front face 95. Reference letter B denotes the phase length of the path of a ray emanating from the focus 98 and propagated to the periphery so as to avoid the lens and reach the front face 95. In order to convert the spherical wave front 102 originating at the focus 98 into a plane wave front 103 at the front face 95, A and B must be equal. Now

$$A=\frac{f}{v_0}+\frac{x}{v} \qquad (10)$$

and

$$B=\frac{\sqrt{(f+x)^2+y^2}}{v_0} \qquad (11)$$

where

f is the focal length of the lens.
x is the lens thickness along the axis 97.
y is the radius or half-aperture of the lens 70.
v is the phase velocity in the lens.
v_0 is the phase velocity in free space.

Hence

$$\frac{f}{v_0}+\frac{x}{v}=\frac{\sqrt{(f+)^2+y^2}}{v_0} \qquad (12)$$

or, since

$$n=\frac{v_0}{v} \qquad (13)$$

where n is the refractive index, we have

$$(n^2-1)x^2+fx(n-1)-y^2=0 \qquad (14)$$

which is the equation for a hyperbola, the origin O, O being at the vertex of the curve or convex face 95. The hyperbolically convex-plano lens shape is disclosed and claimed in my concurrently filed application, Serial No. 748,447.

In operation, Fig. 11, assuming the device 101 is a transmitter, energy is supplied by the transmitter 101 over guide 100 to the horn 99 and a wave having a vertical polarization 21 and a spherical wave front 102, is propagated towards the lens 50. The phase of the wavelets passing through the thick central or vertex portion of the lens are retarded a greater amount than the phase of the wavelets propagated through the outer thinner lens portion, and the wavelets arriving at the flat front face 95 are cophasal. Stated differently, the outgoing spherical wave front 102 is converted by the lens 70 to a plane wave front 103 extending perpendicular to the axis 97. In reception, the converse operation is obtained, and an incoming plane wave front 103 having a propagation direction parallel to the axis 97 is transformed by the positive plano-convey lens 70 into a spherical wave front 102 converging on the focus 98. In other words, the incoming parallel rays 104 and 105 are bent or refraction by the lens, as shown by the rays 106 and 107, and focussed on the primary antenna 99. Inasmuch as the lens 70 is circularly symmetrical, focussing action is obtained in all planes containing the axis 97. As in the prism of Fig. 7, only waves or wave components electrically polarized parallel to the width dimension W of the strips are refracted, the waves polarized perpendicular to the aforesaid dimension being reflected.

If desired, the flat surface of the lens 70, Fig. 11, instead of the convex surface, may face the focus 98 and conical horn 99. In this alternative arrangement, illustrated by Fig. 16, the curvature of the convex face differs from that of the convex face illustrated by Figs. 11 and 15. More particularly, and as disclosed and claimed in the copending application of A. M. Skellett Serial No. 717,214, filed December 19, 1946, now United States Patent 2,547,416, granted April 3, 1951, with the flat lens surface 98 facing the horn, the curvature of the convex surface 95 is obtainable from the following equations in parametric form

$$d=\frac{D(n-1)+f-\sqrt{f^2+r^2}}{n-\sqrt{1-\frac{r^2}{n^2(f^2+r^2)}}}\left(\sqrt{1-\frac{r^2}{n^2(f^2+r^2)}}\right) \qquad (15)$$

$$D=\frac{\sqrt{f^2+(R_{max})^2}-f}{n-1} \qquad (16)$$

$$R=r\left(1+\frac{d}{\sqrt{n^2(f^2+r^2)-r^2}}\right) \qquad (17)$$

where n is the refractive index and r is a parameter, and the terms R_{max}, R, D, d, r and f represent the distances indicated in Fig. 16.

Referring to Fig. 17, reference numerals 110, 111 and 112 denote respectively the E-plane directive patterns taken over a 12 per cent band and, more specifically, at 3860, 4120 and 4360 megacycles corresponding, respectively, to wavelengths of 7.76, 7.28 and 6.89 centimeters, for a system similar to that illustrated by Figs. 11 and 15. In the tested system, a lens 70 having a diameter or aperture of three feet and comprising conductive sheet metal strips having a thickness of 0.005 of an inch was utilized. The strip width W and the spacings S_z and S_y were, respectively, three-quarters of an inch, three-eighths of an inch and one and one-half inches. As shown in Fig. 17, the half-power widths 113 of the major lobes 114 of the three patterns 110, 111 and 112 are the same, namely, 4.5 degrees, so that the directive action is uniform over a very wide band of frequencies. In addition, the minor lobes 115 in the three patterns are down from or below the major lobe peak about the same amount, namely, about 15 decibels. It may be added that, for wavelengths of 7 and 8 centimeters, the measured refractive indices of the tested lens 70 were about 1.43 and 1.41, respectively, and the index n calculated in accordance with Equation 8 was 1.45. Accordingly, the measured and calculated values of n are substantially equal or at least comparable.

Referring to Fig. 18, reference numeral 120 denotes a unipolarized metallic-delay lens which is similar to the lens 70 of Fig. 11, the primary difference between the two lenses being that the lens 120 is cylindrically symmetrical and has a line focus 121, whereas the lens 70 is circularly symmetrical and has a point focus 98. Also, the lens 120 has an optical axial plane 122, whereas the lens 70 has an optical axis 97. The front face 123 of the lens 120 is flat and the back face 124 is cylindrically convex, the convex curvature being determined in accordance with Equation 14. The lens 120 comprises an array 125 of conductive strips 3 spaced in the medium 32 along the Y and Z dimensions and arranged in tiers 79 to 86, the tiers being supported or retained in slots in individual foam slabs 87 to 94. The strips 3 have equal lengths and are mounted in slots having equal lengths corresponding to the strip length. Numeral 126 denotes a sectoral horn having its mouth orifice 127 aligned with the focal line 121, the mouth orifice being equipped with the flares 128. The horn 126 is connected by guide 100 to the translation device 101. The polarizability α_m and the refractive index n, of the lens 120, for waves having an E-vector 21 parallel to the strip width 3, are the same, respectively, as the polarizability and index of the lens 70, Fig. 11.

In operation, Fig. 18, assuming the E-vector 21 is vertical and the focal line 121 is horizontal, waves supplied by device 101 over guide 100 to the horn 126 are projected toward the reflector 120 in the form of a vertical fan-beam, the beam being wide in the vertical plane and narrow in the horizontal plane. The lens 120 functions to focus the waves in the vertical plane, but does not focus the waves in the horizontal plane, that is, the lens 120 has a horizontal fan-beam characteristic. Hence, the outgoing beam from the system comprising the horn or primary antenna 126 and the lens or secondary antenna 120 is narrow in both the vertical plane and the magnetic plane, or, in other words, the system has a point-beam characteristic.

Referring to Figs. 19 and 20, reference numeral 130 denotes a unipolarized, circularly symmetrical, strip lens of simple lightweight construction. The lens 130 comprises six cellophane panel sheets 131, 133, 135, 137, 139 and 141, and five solid dielectric, cellophane or polystyrene foam, spacer sheets 132, 134, 136, 138 and 140, a spacer sheet being positioned between adjacent panel sheets. Each panel sheet contains a circular lens panel 142 comprising a plurality of conductive tin foil strips 3 fastened to the front surface of the panel sheet. The panels have graded diameters, and hence different pluralities of strips, in conformity with the convex optical back face 96 of the lens 130. As in the grid prism of Fig. 10, the corresponding strips in adjacent panels are not aligned, but are staggered. Thus, the eight strips 3 of panel sheet 133 are staggered relative to the nine strips 3 on panel sheet 131, and are therefore opposite the eight spaces 143 of panel sheet 131. Also, the lens axis 97 passes through the central strip 3 of panel sheet 131 and the through spacing 143 between the two central strips 3 on panel sheet 133. The panel and spacer sheets are held together by means of the wooden ring 144, wooden ring 145 and the bolt-and-nut assemblies 146; and the lens is supported by the stand 147. As in the structures previously described, the refractive index n is greater than unity for waves having the E-vector 21 and is dependent upon the values selected for the factors W and N. The lens 130 has a point focus 98 and its convex face is toward the horn 99.

The operation of the system 130, 99, Fig. 19, is the same as that of the system 70, 99 of Fig. 11. Thus for waves electrically polarized parallel to the strip width W, the lens focusses the waves in all planes containing the optical axis 97 and the system 130, 99 has a point-beam characteristic.

Referring to Figs. 21, 22 and 23, reference numeral 150 denotes a unipolarized, circularly symmetrical, grid lens of simple lightweight construction. The lens 150 comprises an array 151 of 39 horizontal grid members 26 each comprising a plurality of vertical metallic rod elements 27. The rods 27 are spaced a distance S_x smaller than a half wavelength apart and have lengths corresponding to the grid width W. The grids 26 are arranged in seven circular vertical panels 152, 153, 154, 155, 156, 157 and 158 extending parallel to the XY plane. The panels 152 to 158 have graded diameters and the component rods 27 are disposed and arranged so that the outermost surfaces of the outermost rods lie in and substantially define the contour of a predetermined conventional shape of wave refractor, such as, for the present example, that of a plano-convex lens.

Alternatively the structure of Figs. 21, 22 and 23 can be considered as one in which the grids are arranged in 11 plano-convex vertical curtains 159 to 169 extending parallel to the YZ plane. In the XY plane the grids are staggered and arranged in 15 horizontal tiers 170. More specifically, panels 152, 153, 154, 155, 156, 157 and 158 have, respectively, eight, seven, six, seven, six, five and two tiers, the grids in adjacent tiers or in adjacent panels being staggered. The rods 27 are mounted in vertical polystyrene foam slabs 171, one for each of curtains 159 to 169, as shown in the expanded perspective view of Fig. 23, and the slabs extend parallel to the YZ plane and are spaced the same horizontal distance S_x, as the rods. The S_y and S_z spacings of the grids 26 are each smaller than a wavelength and, as in the structures of Figs. 3 and 5, preferably less than a half wavelength. The slabs 171 are held in position by means of the single wooden ring 148. As before, the refractive index n of the lens 150 is greater than unity for waves having the vertical E-vector 21 and is dependent upon the values selected for W and N. The lens 150 has a point focus 98 and is unipolarized; and its convex face 96 is toward the horn 99.

The operation of the system, Fig. 21, comprising the lens 150 and the horn 99 is the same, for waves having the E vector 21, as that of the system 130, 99, Fig. 19, and as that of the system 70, 99, Fig. 11. As regards the H-vector components, if any, these components pass through the grid lens 150, Fig. 21, whereas they are reflected by the lens 70 and the lens 130. If desired, matching sections of tapered dielectric constant may be utilized on each face of the lens 130 and 150 in order to minimize the reflection losses, if any.

The type of construction utilized in the strip lens 130 Fig. 19 and the grid lens 150, Fig. 21, permits a relatively close spacing S_z. By reason of the close spacing, and also by virtue of the staggered arrangement, a high effective dielectric constant, and therefore a high delay, are obtainable. The measured effective dielectric constants of a strip array and a grid array, constructed in accordance with Figs. 19 and 21, were 225 and 20, respectively. The strip type artificial material having a dielectric constant of 225 is especially suitable for use in a traveling wave tube, since the corresponding refractive index is 15 and a tube filled with the aforesaid material would have a phase velocity v of

$$\frac{v_0}{15}$$

that is, $\frac{1}{15}$ the velocity in free space.

Referring to Figs. 24 to 30, reference numeral **180** denotes a large unipolarized, circularly symmetrical strip lens having a square periphery **181** and positioned at the mouth orifice **182** of a square pyramidal metallic horn **183**. The lens has an optical axis **97**, a focal point **98** and, as explained below, an unstepped multiple-zone inner or central section **184**, an unstepped multiple-zone outer section **185**, a plane offset front face **186** and a stepped convex offset back face **187**. The center of the horn throat orifice **188** is coincident with the focal point **98** of the lens, and the throat orifice is connected by the rectangular guide **189** to a translation device **191**, such as a super-short wave transmitter or receiver. The flare angles of the horn sides, in the E and H planes, are such that, if the sides were extended to the front face **186**, as shown by the dotted lines **190**, Fig. 27, the four horn sides would just touch the circular periphery of the inner or central zone **184**. In order to permit utilization of the lens **180** and the horn **183** with five, six or seven-centimeter waves corresponding to guides **100**, and throat orifices **183** of different size, the small throat section **191** of the horn is made removable. Hence, a throat section **191** containing a throat orifice **188** of given size may be removed, and another throat section **191** containing a throat orifice **188** of different size may be inserted in its place.

The lens **180** includes an array comprising a large plurality, say 1200, assuming the lens is six foot square, of horizontal sheet metal strip members **3** spaced a distance S_y along the Y dimension, and a distance S_z along the Z dimensions of the lens. The strips are arranged in a large number, say 40, of vertical panels **192** (XY plane), Fig. 30, or stated differently, in a large number, say 60, of horizontal tiers **193** (XZ plane). As in the lens of Fig. 11, the tiers are supported in horizontal polystyrene foam rectangular slabs **194**, one for each tier, the strip members **3** being mounted in individual retaining slots in the slabs. The vertically stacked slabs **194** are held in position by means of the square wooden frame **195**.

The diameter or aperture of the circular central section **184** is ordinarily, but not necessarily, sufficiently large so that the unstepped central section **184** includes several wavelength zones or steps, whereby this section may be stepped, if desired, for the purpose of reducing the thickness or Z dimension of this central section **184**. Similarly, the diagonal dimension of the square lens is ordinarily sufficiently large so that the unstepped outer section **185** includes several wavelength zones, whereby this section may also be stepped, if desired, for the purpose of reducing the thickness of the outer section **185**. While, as shown, the outer section is stepped relative to the central section, each of these sections taken by itself is not stepped inasmuch as stepping a lens having a refractive index independent of frequency, such as lens **180**, reduces the band width, as in the case of a parabolic reflector. By way of contrast, stepping a lens, such as a fast metallic lens, having an index which varies rapidly with frequency increases the bandwidth. The step **196** between the two sections is of the intermediate type disclosed in my copending application, Serial No. 642,723 mentioned above. If desired, however, the step **196** may be of the horizontal type or of the focal type, both also disclosed in the last-mentioned application. As will now be explained, the convex curvature for the outer section **185** differs from the convex curvature of the central section **184**.

Referring to Fig. 30, it is assumed that the ray **197** from the focus **98** travels a distance T through free space and arrives at the front face **186** of the lens **180**, whereas the ray **198** from the focus **98** travels the same distance T through the artificial delay material or metallic array and arrives at the front face **186**. Now

$$t_1=\frac{T}{v_0} \tag{18}$$

and

$$t_2=\frac{T}{v} \tag{19}$$

where

t_1 is the time the ray **197** takes to travel the distance T in free space,
t_2 is the time the ray **198** takes to travel the distance T in the metallic delay array,
v_0 is the phase velocity in free space, and
v is the phase velocity in the lens **180**.

Since,

$$v_0>v \tag{20}$$

we have,

$$t_2>t_1 \tag{21}$$

But, in order for rays **197** and **198** to arrive in phase at the lens face **186**,

$$t_2-t_1$$

must equal

$$K\lambda_0$$

where K is any integer and λ_0 is the mid-band wavelength in free space.

That is,

$$t_2-t_1=K\lambda_0 \tag{22}$$

or

$$t_1=t_2-\frac{K\lambda_0}{v_0}$$

Substituting

$$\frac{T}{v_0}=\frac{T}{v}-\frac{K\lambda_0}{v_0} \tag{23}$$

$$-\frac{T}{v_0}+\frac{T}{v}=\frac{K\lambda_0}{v_0} \tag{24}$$

$$-T+T\frac{v_0}{v}=K\lambda_0 \tag{25}$$

$$T(n-1)=K\lambda_0 \tag{26}$$

$$T=\frac{K\lambda_0}{n-1} \tag{27}$$

As already indicated, referring to Fig. 15, Equation 14 defines the convex contour **199** of the central section **184**, the origin O, O being taken at the vertex of the curve. Consequently, by adding T as given by Equation 27 to the value of X, and subtracting it from f, in Equation 14, we obtain the following equation for the convex contour of the back face of the outer section 185.

$$(n^2-1)\left(X+\frac{K\lambda_0}{n-1}\right)^2+2\left(f-\frac{K\lambda_0}{n-1}\right)\left(X+\frac{K\lambda_0}{n-1}\right)(n-1)-y^2=0 \quad (28)$$

In practice, the particular value for K is utilized which brings the convex contour of the outer section nearest to the corners of the horn.

In order to eliminate the reflection, if any, of energy from the front and back faces of the lens into the guide 189, the upper half of the lens is offset, horizontally, a distance D equal to one-quarter of the mid-band wavelength, or an odd multiple thereof, relative to the bottom half of the lens.

The operation of the lens 180 is basically the same as that of the lens of Fig. 11. Thus, waves having a vertical E vector 21 parallel to the width dimension of the strips are delayed and refracted, and focussing in all planes containing the axis 97 is obtained. Waves having a horizontal E vector are reflected at the faces of the lens. The horn sides function to shield the lens whereby, as discussed in more detail below, the minor lobes are reduced and a highly satisfactory directive characteristic is obtained. By reason of the quarter wave offset D the wavelets reflected from the top half of the lens are displaced 180 degrees in time phase relative to those reflected by the lower half, and substantially no reflected energy enters the guide 189.

A shielded lens system constructed in accordance with Figs. 24 to 30 was tested at frequencies included in the 3900 to 4300 megacycle band. In the tested system, the X and Y dimensions of the lens were each six feet, the lens thickness or Z dimension was sixteen inches and the focal length f was about five feet. The width W of the strips 3 and the strip spacings S_x and S_z were, respectively, about 0.75, 1.31 and 0.375 inch, corresponding to 0.25, 0.46 and 0.13 of the mid-band or intermediate wavelength of 7.2 centimeters; and the strip thickness was 0.005 inch. The measured index of refraction n of the lens 180, with the strip width and strip spacings mentioned above, was about 1.50. As discussed below, Figs. 31 to 35 illustrate the measured characteristics of the tested system 180, 183, just described.

Referring to Figs. 31 and 32, reference numerals 200 and 201 denote the H or horizontal plane directive patterns, both measured at a wavelength of about 7.2 centimeters, for the tested lens 180 taken by itself, that is, without the shields or horn sides, and for the tested lens 180 with the horn sides, respectively. Numerals 202 and 203 designated the major lobes, and numerals 204 and 205 denote the minor lobes, of patterns 200 and 201, respectively. Each pattern, it will be observed, is highly symmetrical about the axis 97. The symmetry indicates a high degree of homogeneity of the artificial dielectric material or array, a quality or property not always found in solid dielectric substances, such as polystyrene. As shown in Fig. 31, the half-power width 206 of the major lobe 202 is about 2.6 degrees and the half-power width 207 of the major lobe 203 is approximately 2.68 degrees. The beam or half-power width is, of course, a function of the lens aperture and for a larger aperture as, for example, 10 feet, the beam would be considerably more narrow. The minor lobes are exceedingly low and are generally smaller, as is desired, than the minor lobes in the patterns of comparable prior art structures. Thus, even in the pattern 200 for the six-foot unshielded lens, the minor lobes 204 are about 28 decibels down, that is, below the peak of the major lobe 200. In the pattern 201 for the six-foot shielded lens, the minor lobes 205 are more than 35 and almost 40 decibels down. Undoubtedly, if the lens aperture were 10 feet the minor lobes would be still lower. By way of comparison, the minor lobes for the shielded dielectric channel fast lens disclosed in my copending application Serial No. 642,723 are about 25 to 30 decibels down. While the patterns 200 and 201 are horizontal plane patterns, each pattern represents fairly accurately the pattern for any other plane containing the axis 97. In practice, the major lobe of the vertical plane pattern is usually slightly more narrow than major lobe 202 or 203, and the minor lobes are more pronounced inasmuch as the waves are polarized in the vertical plane and, accordingly, the illumination of the lens by the throat orifice is tapered less in this plane than in the horizontal plane.

Referring to Figs. 33 and 34, the curve 210 denotes the absolute gain of a standard horn over the wide frequency band 3920 to 4300 megacycles and numeral 211 designates the measured gain, over the standard horn, of the actually constructed shielded lens 180, 183. Since, during the test, the field strength varied along the horn mouth orifice or lens aperture, but did not vary in the orifice of the standard horn, a correction is applied to the curve 211. Reference numeral 212 denotes the corrected gain curve for the shielded lens 180. The gain for the ideal or optimum isotropic antenna having an area corresponding to that of lens 180 is represented by the curve 213. The difference in the gain curves 212 and 213 is a measure of the efficiency of the shielded lens; and the curve 214, Fig. 34, represents this measured difference. For comparison purposes, the measured efficiency curve 215 of a shielded metallic-advance channel lens is shown in Fig. 34. The mid-band gain or efficiency, taken at 4220 megacycles, of the shielded metallic-delay lens of the invention is about one decibel better than that of the metallic-advance lens. Also, by reason of the fact that the refractive index n of the lens of the invention is constant with frequency, the gain curve 214 is flat, that is, the gain is uniform, over the 500 (4420 minus 3920) megacycle band. On the other hand, the index n of the metallic-advance lens varies with frequency and the gain is not uniform over the band.

Referring to Fig. 35, reference numeral 216 denotes the measured frequency-matching characteristic for the horn 183, Fig. 24 and numeral 217 designates the frequency-matching curve of the lens 180 as attached to the horn 183. As shown by the curves the standing wave ratios or characteristics 216 and 217, as measured in the guide 186, do not vary substantially over the band, as is desired. Thus, the ratio or curve 216 for the horn varies less than 0.4 decibel and the ratio 217 for the shielded lens varies about 0.3 decibel.

Although the invention has been described in connection with certain embodiments, it is to be understood that it is not to be limited to the embodiments described inasmuch as other apparatus may be successfully employed in practicing the invention.

What is claimed is:

1. A metallic electromagnetic phase velocity changer comprising flat rectangular conductive

members having equal width dimensions extending in a direction parallel to the electric polarization of an incoming electromagnetic wave and spaced apart in a direction coincident with said width dimensions, said structure having an effective dielectric constant greater than unity and dependent upon the aforesaid width dimensions of said members.

2. A metallic array for retarding an electromagnetic wave having a given wavelength, a given propagation path and given electric and magnetic polarizations, said array comprising conductive members spaced in a dielectric medium along directions parallel to said propagation path and said electric polarization of said wave, the length and width of said members being parallel to said magnetic and electric wave polarizations, respectively, the spacing between adjacent members and the width of each member being dependent upon and smaller than one-half of said wavelength.

3. An array in accordance with claim 2, said array having an effective dielectric constant greater than unity and dependent upon the spacing and width of said members.

4. A plano-convex metallic lens for refracting an electromagnetic wave, said lens comprising a polystyrene foam medium and flat conductive strip members spaced in said medium along directions parallel to the electric polarization and the propagation path of said wave.

5. A lens in accordance with claim 4, said lens being circularly symmetrical and having a point focus.

6. A lens in accordance with claim 4, said lens being cylindrically symmetrical and having a line focus.

7. In combination, a lens for refracting electromagnetic waves included in a given band of wavelengths, said lens having an axis and a focus, a primary antenna at said focus, one-half of said lens being displaced relative to the other half, and along said axis, one-quarter of the mean wavelength in said band, or an odd multiple thereof.

8. A plano-convex, circularly symmetrical, stepped radio lens comprising an array of conductive strips extending parallel to the magnetic vector of an incoming plane polarized electromagnetic wave, the outermost surfaces of the outermost strips of said array being positioned to substantially define the exterior contours of said plano-convex, circularly symmetrical, stepped radio lens, the widths of said strips and the spacings therebetween being proportioned to produce

a predetermined effective dielectric constant for said lens.

9. A hyperbolically convex-plano, circularly symmetrical, lens for refracting a super-short radio wave included in a given band, said lens having a refractive index greater than unity and an optical axis, said lens comprising an inner zone and an outer stepped zone, each zone comprising a plurality of flat conductive strip members having longitudinal dimensions extending parallel to the magnetic polarization of said waves, the width dimension of said members being smaller than one-half the minimum wavelength in said band and extending parallel to the electric polarization of said waves, said members being arranged in tiers extending parallel to said axis, each tier being mounted in a polystyrene foam slab, the spacing between tiers and the spacing in each tier between the adjacent members being smaller than one wavelength.

10. A lens in accordance with claim 9, the focal length of one-half of said lens being a quarter of the mean wavelength in said band, or an odd multiple thereof, greater than the focal length of the other half of said lens.

11. In combination, a pyramidal horn having square throat and mouth orifices, a translation device connected to the throat orifice of said horn, a stepped plano-convex square metallic lens positioned at the mouth orifice of said horn and having its convex surface facing said throat orifice, said lens having an optical axis coincident with the axis of the horn and a point focus coincident with the center of said throat orifice, said lens comprising a plurality of conductive strips extending perpendicular to said optical lens axis.

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