EXAMINER

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911

Dec. 18, 1951 W. E. KOCK 2,579,324

METALLIC STRUCTURE FOR DELAYING PROPAGATED WAVES

Filed May 16, 1947 6 Sheets-Sheet 1

FIG. 1

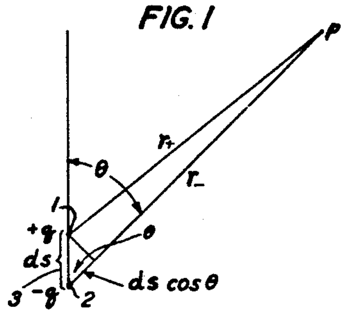


FIG. 2

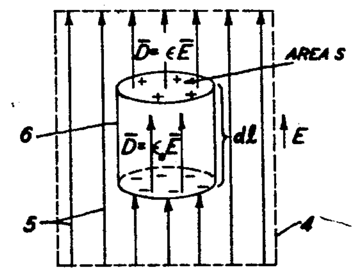


FIG. 7

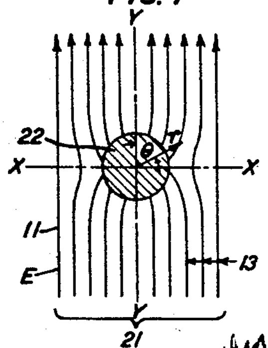


FIG. 8

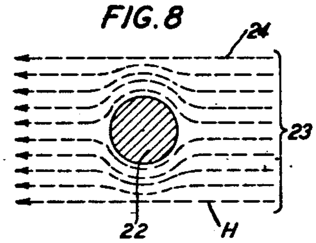
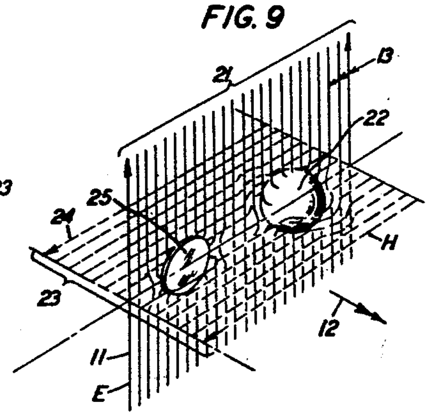


FIG. 9



smaller than λ/4

METALLIC PARTICLES

POLYSTYRENE FOAM

FIG. 4

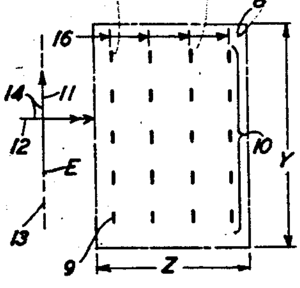


FIG. 5

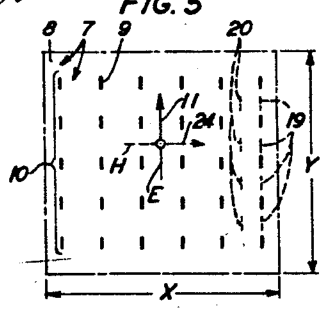


FIG. 6

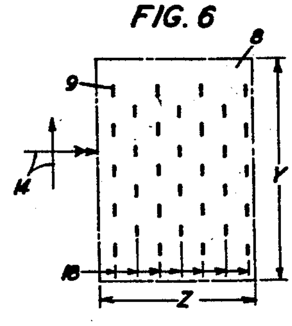
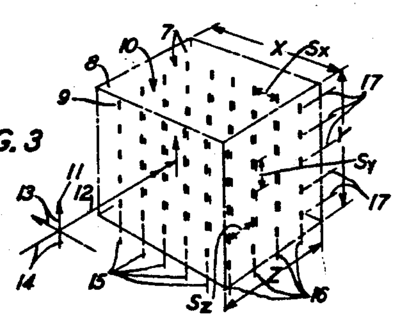


FIG. 3



INVENTOR
W. E. KOCK
BY A. J. Zerbarini
ATTORNEY

SEE: KOCK 2,577,619 343-753
SEE BR 655747 343-753

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Dec. 18, 1951 W. E. KOCK 2,579,324

METALLIC STRUCTURE FOR DELAYING PROPAGATED WAVES

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FIG. 11

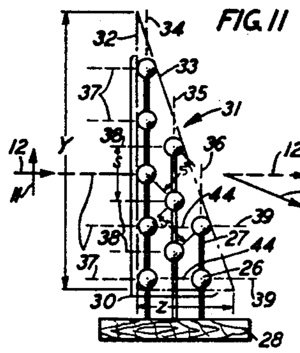


FIG. 10

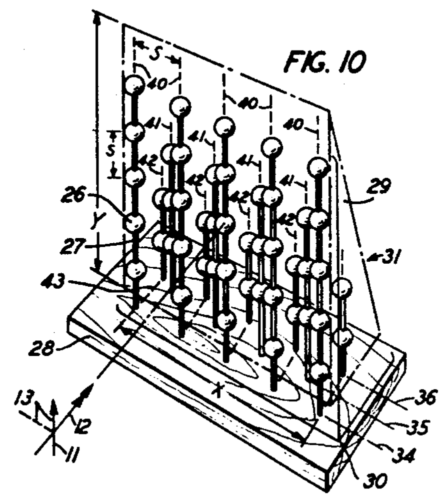


FIG. 13

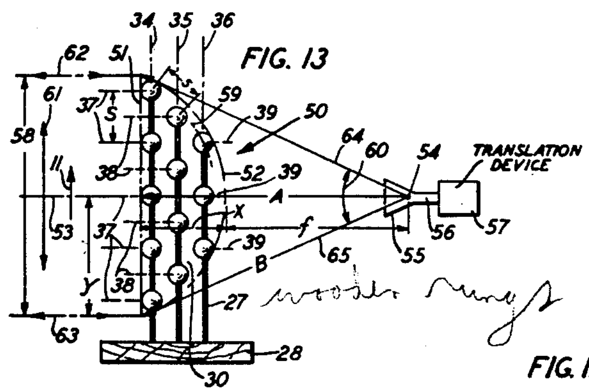


FIG. 12

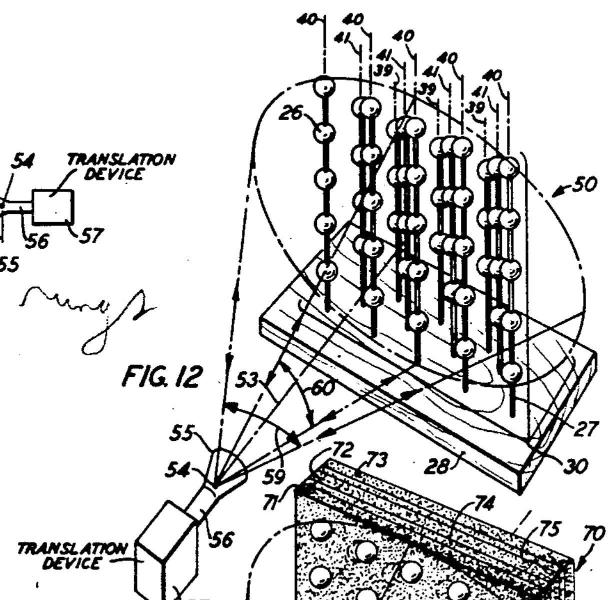


FIG. 15

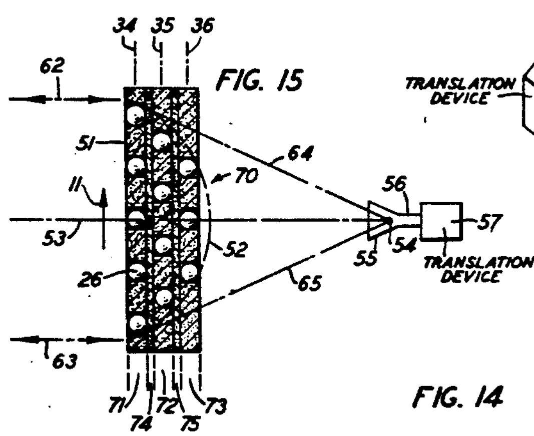
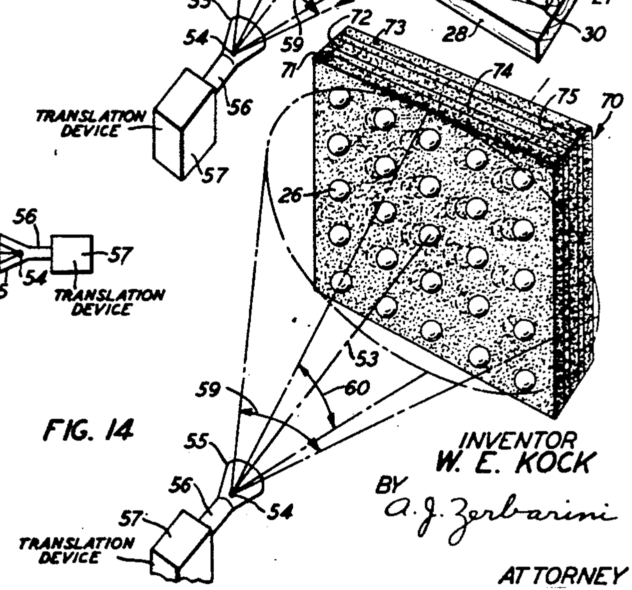


FIG. 14



INVENTOR
W. E. KOCK
BY
A. J. Zerbarini
ATTORNEY

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METALLIC STRUCTURE FOR DELAYING PROPAGATED WAVES

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FIG. 16

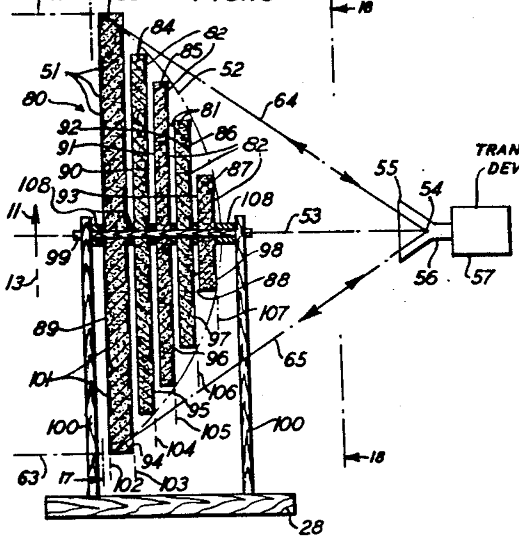


FIG. 17

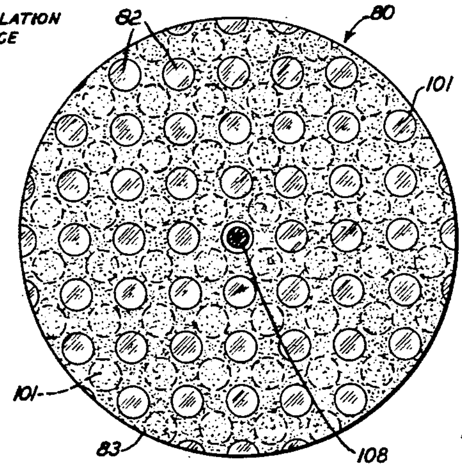


FIG. 18

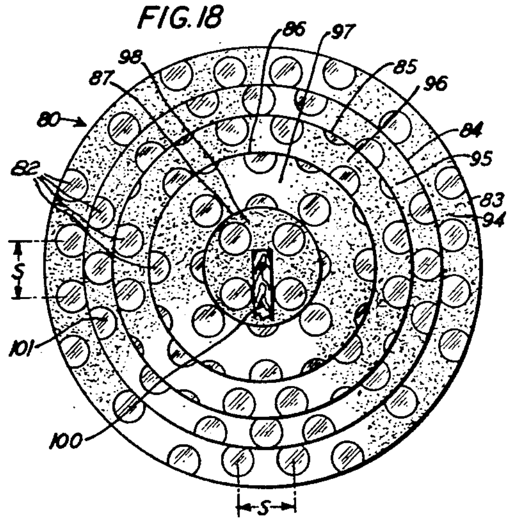
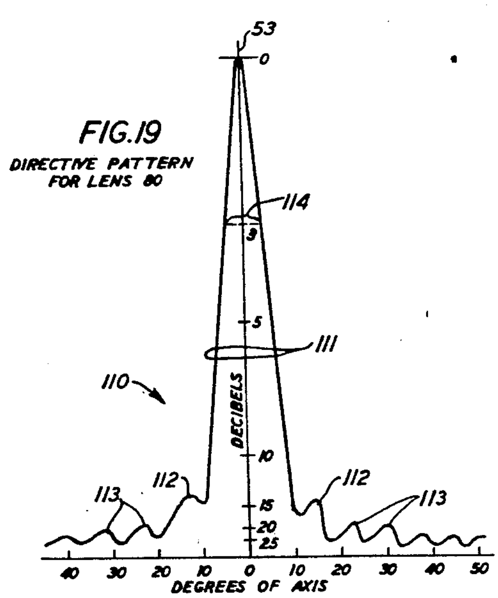


FIG. 19

DIRECTIVE PATTERN FOR LENS 80



INVENTOR
W. E. KOCK
BY A. J. Zerbarini
ATTORNEY

EXAMINER

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METALLIC STRUCTURE FOR DELAYING PROPAGATED WAVES

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FIG. 21

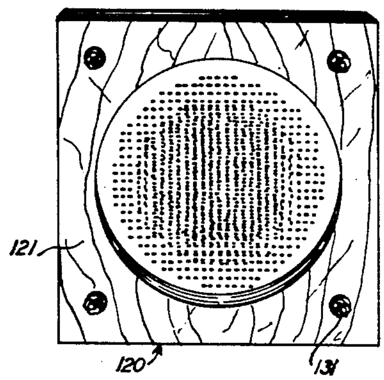


FIG. 20

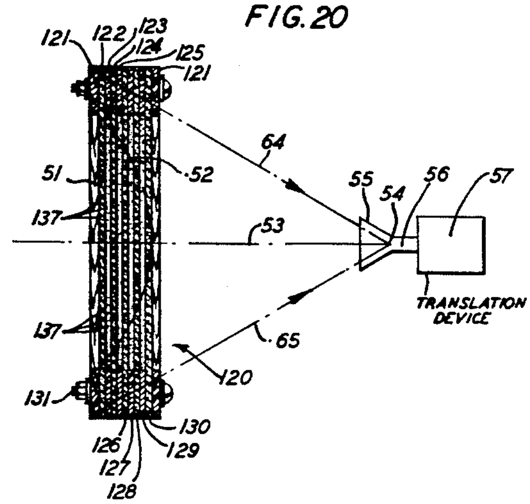


FIG. 23

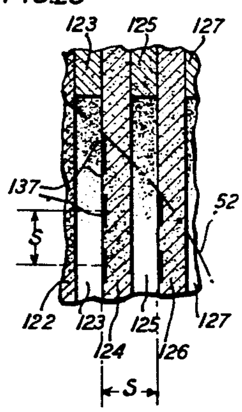
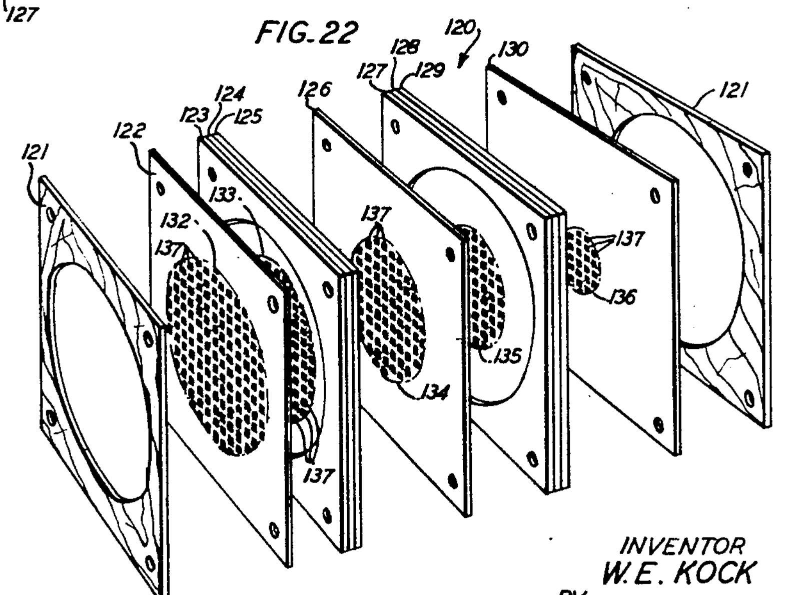


FIG. 22



INVENTOR
W. E. KOCK
BY A. J. Zerbarini
ATTORNEY

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METALLIC STRUCTURE FOR DELAYING PROPAGATED WAVES

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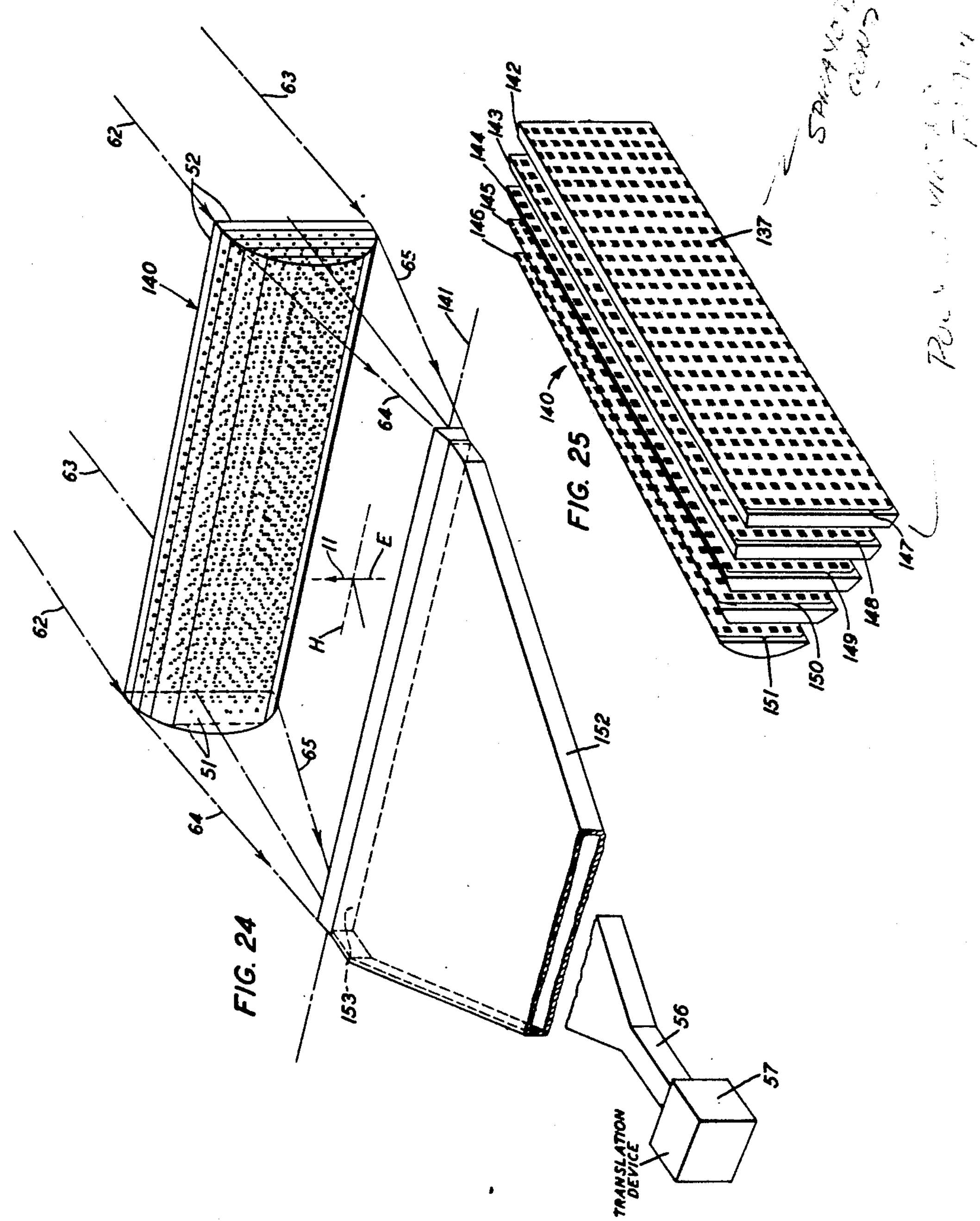

FIG. 24

FIG. 25

INVENTOR
W. E. KOCK
BY A. J. Zerbarini
ATTORNEY

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METALLIC STRUCTURE FOR DELAYING PROPAGATED WAVES

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FIG. 26

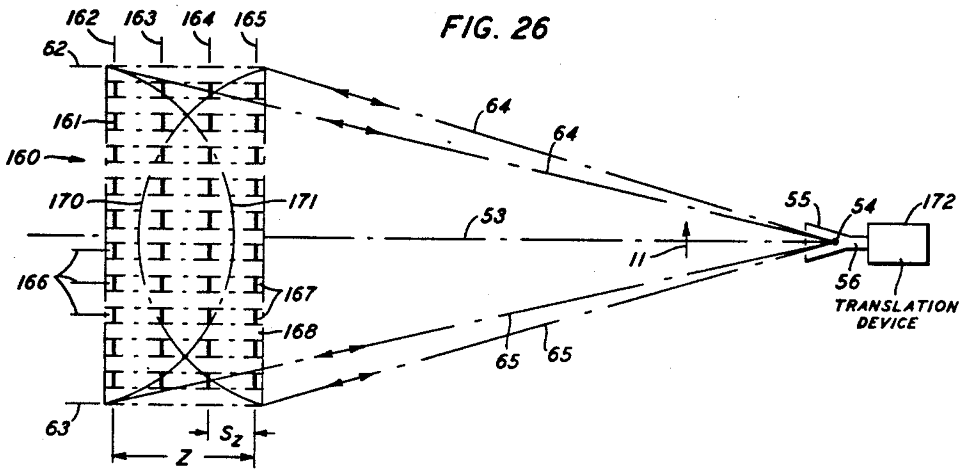


FIG. 27

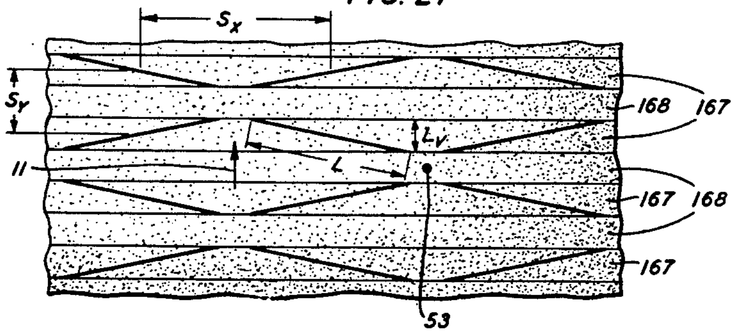


FIG. 28

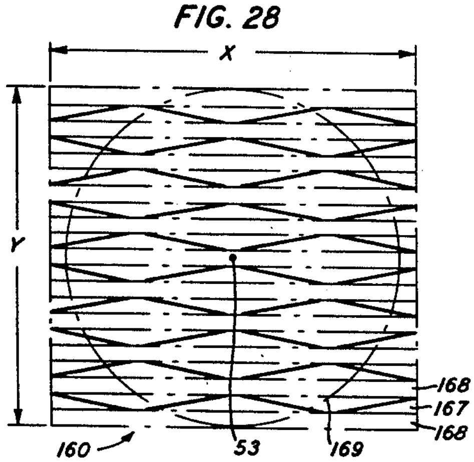
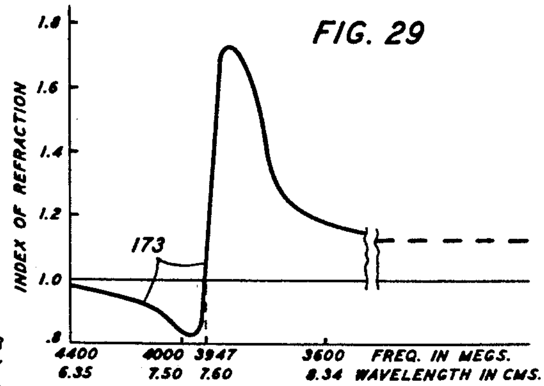


FIG. 29



INVENTOR
W. E. KOCK
BY A. J. Zerbarini
ATTORNEY

Patented Dec. 18, 1951 **2,579,324**

UNITED STATES PATENT OFFICE

2,579,324

METALLIC STRUCTURE FOR DELAYING PROPAGATED 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. 748,447

8 Claims. (Cl. 250—33.63)

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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 phase velocity changers comprising iron conductors immersed in a solid dielectric substance have been suggested for generating short radio waves (10–185 meters) 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 or bending the propagation direction of radio waves. 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 passive wires, and Fig. 21 of Patent 2,283,935 granted to A. P. King on May 26, 1942, illustrates a horn antenna having a solid dielectric delay lens in its mouth orifice. In addition, as disclosed in my copending applications, Serial Nos. 642,722 and 642,723, both filed on January 22, 1946, metallic-advance lenses comprising air dielectric channels have been suggested for use in very-short wave (1–10 meters), ultra-short wave (10–100 centimeters) and super-short wave or microwave (1–10 centimeters) antenna systems.

In general, the solid dielectric delay lens is isotropic; and since the dielectric constant, and therefore the refractive index, of the delay lens do not vary appreciably with frequency, in the frequency region in which they are employed, the lens has a relatively broad band width. On the other hand, the end-on array mentioned above is frequency sensitive since the wires are only slightly shorter than one-half the operating wavelength. The metallic-advance lens also has a fairly narrow band width, since the refractive index is dependent primarily on the width or "*a*" dimension of the channel and the channel width varies rapidly with frequency. While the metallic-advance lens may be designed for two polarizations, ordinarily these lenses are suitable for utilization with only a single polarization.

The metallic-advance refractors have, however, distinct advantages not found in the metallic-dielectric phase velocity changer or the solid dielectric lens. Thus the prior art metallic-

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dielectric and solid dielectric structures are relatively heavy and difficult to manufacture. Moreover, the attenuation of the waves passing through these structures is considerable. In addition, in the case of the solid dielectric lens, the amount of reflection at the two surfaces of the dielectric material, is usually fairly high, with the result that the total energy loss is appreciable and the directivity gain of the lens is not relatively high. On the contrary, the aforesaid metallic-advance lenses are lightweight and substantially lossless; and the directivity gain is high, that is, considerably greater than that of the solid dielectric lens. Accordingly, it now appears desirable to obtain refractors, and particularly lenses, which possess the advantages, but are devoid of the disadvantages, inherent in the above-mentioned prior art structures. In particular, it appears desirable to obtain a metallic lens having distinctive attributes not found in the lenses and other structure heretofore utilized.

It is one object of this invention to alter the phase velocity of an electromagnetic wave in a more efficient and satisfactory manner than heretofore accomplished.

It is another object of this invention to refract radio waves in a more efficient and satisfactory manner than heretofore accomplished.

It is another object of this invention to focus, with only negligible loss, electromagnetic waves included in an exceedingly large band of wavelengths.

It is another object of this invention to obtain, in a metallic lens, a high gain, broad band isotropic or quasi-isotropic characteristic.

It is still another object of this invention to obtain, in a refractor, a refractive index greater or smaller than unity, dependent upon the frequency of the wave propagated through the refractor.

It is a further object of this invention to obtain a broad band refractor which, as compared to broad band refractors heretofore utilized, is lighter, more easily constructed and less expensive.

In accordance with one embodiment of the invention a metallic-delay assembly or array for refracting radio waves comprises small spherical conductive elements having diameters of about three-eighths of an inch and spaced, center to center, about three-fourths of an inch apart and along three dimensions in a dielectric medium or binder, such as polystyrene foam. The diameter of each sphere, and hence the linear dimension of each element as measured in a direction parallel to the electric (E) vector or polarization of the refracted waves, and the spacing between the spheres, are considerably smaller than one-half of the minimum wavelength in the operating band, the aforesaid E vector dimension being preferably a quarter wavelength or less. The foam has a dielectric constant substantially equal to unity and hence does not materially affect the phase velocity of the waves. The effective dielectric constant of the three dimensional array of conductive elements is a function of the polarizability of a typical individual element and the number of elements dispersed in a unit volume of the structure comprising the foam and the array; and it is greater than unity. Hence the refractive index of the structure is greater than unity so that, in operation, the structure functions to delay or retard the phase velocity of the waves propagated therethrough. The metallic delay structure is truly isotropic inasmuch as for all possible E vector directions, and therefore irrespective of the wave propagation direction, a diameter of each sphere is aligned with the E vector. In one embodiment the structure is shaped so as to constitute a plano-hyperbolically convex diverging or positive lens. In another embodiment, the structure is shaped like a prism.

In still another embodiment of the invention, thin conductive disks are used in place of the conductive spheres described above, the flat disk sides extending in the plane of the wave front and the thickness dimension being perpendicular to the E vector. The disk type of metallic-delay structure is anisotropic. In one sense, however, it is quasi-isotropic since the diverse diameters of each disk are parallel only to the diverse possible E polarization directions included in plane of a wave front extending parallel to the disk faces, the wave front being, of course, perpendicular to the wave propagation direction aligned with the optical axis of the structure. The embodiment comprising disks is usually preferred over the embodiment comprising spheres because, in contrast to the spherical elements, the thin disk elements do not appreciably perturb the magnetic lines of force and hence do not decrease, detrimentally, the expected or theoretical value of the refractive index.

If desired, instead of polystyrene foam, a dielectric medium, such as air, vacuum or rubber, may be utilized in the metallic delay structure. If the dielectric constant of the medium is not negligible, the over-all effective dielectric constant of the refractor is dependent upon the proportions, by volume, of the medium and of the conductive array in a unit volume of the refractive structure.

The conductive spheres or disks in the above-described embodiments may, for purpose of explanation, be considered as linear capacitative elements aligned with and spaced along the E vector, and also spaced along the propagation path. Hence, in a sense, they constitute shunt capacitors for loading free space in a manner such as to effect a reduction in the phase velocity of the space wave. Analogously, shunt condensers on a transmission line act as loading elements and function to reduce the wave velocity.

In addition, other embodiments comprising linear wire elements, tilted rod elements and square mote or dot elements of conductive paint are described and claimed herein. Also, it may be added, other types of metallic-delay structures, such as wave changers and lenses comprising solid or grid metallic strips, are disclosed and claimed in my copending application for "Transmission Systems," Serial No. 748,448, filed on May 16, 1947 concurrently with the present application.

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:

Figs. 1 and 2 are explanatory diagrams used in explaining the invention;

Fig. 3 is a perspective view, and Figs. 4 and 5 are respectively, front and side views, of a metallic-delay structure constructed in accordance with the invention;

Fig. 6 is a side view of another metallic-delay structure constructed in accordance with the invention;

Figs. 7, 8 and 9 are also explanatory diagrams used in explaining the invention;

Figs. 10 and 11 are, respectively, perspective and side views of an isotropic metallic-delay prism constructed in accordance with the invention;

Figs. 12 and 13, are, respectively, perspective and side views of a directive antenna system comprising an isotropic metallic-delay, circularly symmetrical, lens constructed in accordance with the invention;

Figs. 14 and 15 are, respectively, perspective and side views of an antenna system comprising another isotropic metallic-delay, circularly symmetrical, lens constructed in accordance with the invention;

Fig. 16 is a side view of an antenna system comprising a quasi-isotropic metallic-delay, circularly symmetrical, lens constructed in accordance with the invention;

Figs. 17 and 18 are, respectively, front and back views of the lens included in the system of Fig. 16, and Fig. 19 is a directive pattern of the system of Fig. 16;

Fig. 20 is a side view of an antenna system comprising another quasi-isotropic metallic-delay, circularly symmetrical, lens constructed in accordance with the invention;

Figs. 21, 22 and 23 are, respectively, a tilted front view, an exploded perspective view and an enlarged detail partial side view of the lens utilized in the system of Fig. 20;

Fig. 24 is a perspective view of an antenna system comprising a quasi-isotropic metallic-delay, cylindrically symmetrical, lens constructed in accordance with the invention, and Fig. 25 is an exploded perspective view of the lens used in the system of Fig. 24.

Fig. 26 is a side view of an antenna system comprising an isotropic circularly symmetrical, frequency sensitive, metallic-delay or metallic-advance lens constructed in accordance with the invention;

Figs. 27 and 28 are enlarged partial side and front views, respectively, of the lens used in the system of Fig. 26, and Fig. 29 is a dispersion curve for the lens of Fig. 26.

Before describing the several embodiments of the invention illustrated on the drawing, the theory underlying the metallic-delay structures will be discussed. Referring to Fig. 1, reference numerals 1 and 2 denote, respectively, oppositely polarized unit or point-charges $+q$ and $-q$, which are displaced from each other a minute distance and which constitute an electric dipole; and numeral 3 denotes the electric vector connecting the charges and having a length $\overline{ds}$. The electric dipole moment, $\overline{m}$, is defined as

$$\overline{m}=q\,\overline{ds} \tag{1}$$

The potential, V, at any point, p, resulting from a point-charge, q, is defined as the work required to move a unit charge from infinity to that point, or

$$V=\frac{q}{4\pi\epsilon r} \tag{2}$$

where r is the distance from the point in question to the charge q, and ϵ is the dielectric constant. If there are several charges present, their fields can be superposed and the potential is given by

$$V=\Sigma_i\frac{q_i}{4\pi\epsilon r_i} \tag{3}$$

In the case of the dipole, Fig. 1, this reduces to

$$V_d=\frac{(+q)}{4\pi\epsilon r_+}+\frac{(-q)}{4\pi\epsilon r_-} \tag{4}$$

where r_+ and r_- are, respectively, the distances from the point p to the positive charge $+q$ and the negative charge $-q$, and V_d is the electric dipole potential. As indicated in Fig. 1

$$r_-=r_++ds\cos\theta \tag{5}$$

so that

$$V=\frac{q}{4\pi\epsilon}\left[\frac{1}{r_+}-\frac{1}{r_++ds\cos\theta}\right] \tag{6}$$

$$=\frac{q}{4\pi\epsilon}\left[\frac{r_++ds\cos\theta-r_+}{r_+^2+rds\cos\theta}\right] \tag{7}$$

$$\approx\frac{qds\cos\theta}{4\pi\epsilon r^2} \tag{8}$$

or, from Equation 1, the potential distribution of a dipole of moment $\overline{m}$ is

$$V_d=\frac{|m|}{4\pi\epsilon r^2_d}\cos\theta \tag{9}$$

Referring to Fig. 2, reference numeral 4 denotes a homogeneous dielectric medium 4 in which a uniform electrostatic field $\overline{E}$ exists, the polarization of the field being represents by the arrows 5. The impressed field E causes a redistribution, that is, a displacement or realignment, of the charges or charged particles in the field, and causes them to simulate electric dipoles.

It may be well to point out here that the dielectric medium or material is assumed to be a "non-polar" or "hetero-polar" dielectric containing molecules which have charges, but no electric dipole moment until an electric field is applied. The polarization of such materials, and the artificial dielectrics considered herein, is accordingly independent of temperature. On the other hand so-called "polar dielectrics" have arrangements of charged particles which are electric dipoles even before an external electric field is applied. The applied field tends to align these dipoles and collisions produced by thermal motion tend to destroy the alignment. Accordingly, the amount of polarization, and hence the dielectric constant, which the particles exhibit depend upon the temperature.

The density of the lines of force, Fig. 2, of the displacement vector $\overline{D}$ will be ϵ times as great as the density of the lines of force of the $\overline{E}$ vector. Now, let us remove a right cylindrical section 6 of the dielectric, the section 6 having its axis parallel to $\overline{E}$, and let us place positive and negative charges at the ends of the space previously occupied by the removed cylinder, in a manner such that the field is not disturbed. Inside the empty space

$$\overline{D}_{in}=\epsilon_0\overline{E} \tag{10}$$

whereas, outside the cylindrical space

$$\overline{D}_{out}=\epsilon\overline{E}=\overline{D},\text{ as before} \tag{11}$$

where ϵ_0 and ϵ are, respectively, the dielectric constant of free space and the dielectric constant of the dielectric medium. Now, a charge $+q$ and $-q$ placed, respectively, on the plates of a parallel plate air condenser of unit area will produce between the plates a field having a magnitude

$$E'=\frac{q}{\epsilon_0} \tag{12}$$

Similarly, the field inside the cylindrical space, and resulting from the added charges q per unit area at its ends, will have a magnitude $\overline{E}'$, as given by Equation 12. Since we postulated that the field be not disturbed $\epsilon_0\overline{E}'$ must equal the difference between D_{out}, Equation 10, and $\epsilon_0\overline{E}$, that is,

$$q=\epsilon_0E'=|\overline{D}|-\epsilon_0|\overline{E}|=\epsilon|\overline{E}|-\epsilon_0|\overline{E}| \tag{13}$$

$$=(\epsilon-\epsilon_0)|\overline{E}| \tag{14}$$

But

$$\epsilon_r=\frac{\epsilon}{\epsilon_0} \tag{15}$$

where ϵ_r is the relative dielectric constant so that

$$q=(\epsilon_r-1)\epsilon_0\,1\overline{E}1 \tag{16}$$

The cylindrical element 6 has at each transverse end an area s, and charges $+qs$ and $-qs$ at its ends. Hence, from Equation 1 we have

$$d\overline{m}=qsdl \tag{17}$$

where

dm is the electric dipole moment of the cylindrical space

dl is the length of the cylinder.

From Equations 16 and 17 we have

$$d\overline{m}=(\epsilon_r-1)\,\epsilon_0\,\overline{E}sdl \tag{18}$$

But

$$sdl=d\tau \tag{19}$$

so that

$$d\overline{m}=(\epsilon_r-1)\epsilon_0\overline{E}\,d\tau \tag{20}$$

where

$d\tau$ is an element of volume.

The electric dipole moment $d\overline{m}$, referred to a unit volume of the medium, is defined as the polarization, $\overline{P}$, of the medium, and we have

$$\overline{P}=(\epsilon-\epsilon_0)\overline{E} \tag{21}$$

$$=(\epsilon_r-1)\epsilon_0\overline{E} \tag{22}$$

Referring now to Figs. 3, 4 and 5, reference numeral 7 denotes a wave delay structure or device comprising a dielectric medium 8, such as air or polystyrene foam and conductive objects 9 as, for example, metallic linear elements spaced along the three dimensions X, Y and Z of the medium 8. The elements 9 form a metallic array or assembly 10, or so-called artificial dielectric material, for delaying the phase velocity of electromagnetic waves. Numerals 11 and 12 denote arrows representing, respectively, the electric polarization and the direction of propagation of the applied electric field E; and numerals 13 and 14 designate, respectively, the plane of the incoming wave front and the vertical plane of wave propagation. In the direction of the electric vector 11, the dimensions of the elements 9 are chosen so as to be small relative to one-half of the minimum wavelength in the propagated band, that is, about a quarter and preferably a much smaller fraction of the aforesaid wavelength, in order to avoid resonant effects which may occur when the element length or dimension parallel to the E vector is in the vicinity of one-half wavelength. The center-to-center spacings S_x, S_y and S_z of the elements 9, along the three dimensions or axes X, Y and Z are preferably equal and less than one wavelength. The spacings between adjacent elements, each of which, as explained below, constitutes an electric dipole, should in any event be greater than the so-called breakdown value or, in other words, sufficiently great to prevent short-circuiting of the elements or dipoles. Moreover, as discussed below, the minimum spacings between the elements may, if desired, be chosen so as to avoid mutual effects or coupling among the elements, substantially. Assuming the elements are dispersed linearly, as illustrated in Fig. 3, the spacings of the elements are dependent upon the selected number of elements per unit volume of the structure 7.

An impressed electric field E having a polarization 11 and a propagation direction 12, produces a redistribution of the charges on the conductive elements 9 and causes them to act like small electric dipoles. Each of these dipoles then possesses a certain electric dipole moment which is related to the impressed electric vector and the polarizability of the individual element 9 by the equation

$$\overline{m}=\alpha\overline{E} \qquad (23)$$

where

$\overline{m}$ is the electric dipole moment,

α is the polarizability of the individual element 9 and

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

Assuming there are N elements per unit volume of the dielectric medium 8,

$$\overline{P}=N\alpha\overline{E} \qquad (24)$$

where

$\overline{P}$ is the polarization, referred to a unit volume, of all the elements 9, that is, of the array 10, as immersed in the dielectric medium 8 having a given total volume XYZ.

But, from Equations 11 and 21

$$\overline{P}=\epsilon\overline{E}-\epsilon_0\overline{E} \qquad (25)$$

$$\overline{P}=\overline{D}-\epsilon_0 E \qquad (26)$$

so that,

$$\overline{D}=\overline{P}+\epsilon_0 E \qquad (27)$$

and from Equations 24 and 27 we have

$$\overline{D}=(\epsilon_0+N\alpha)\overline{E}=\epsilon E \qquad (28)$$

where

ϵ is the effective dielectric constant of the artificial dielectric material or conductive structure 10 comprising all of the elements 9.

ϵ_0 is, as before, the dielectric constant of free space, and

ϵ_r is the relative dielectric constant.

But

$$\epsilon_r=\frac{\epsilon}{\epsilon_0}=n^2 \qquad (29)$$

where

n is the refractive index of the conductive array of elements 9.

Also from Equations 28 and 29, assuming the effective relative permeability μ_r of the structure 10 to be unity, we have

$$n^2=1+\frac{N\alpha}{\epsilon_0}=\epsilon_r \qquad (30)$$

Hence, if the element polarizability, α, is known, the refractive index, n, of the structure 10 may be determined. The theoretical and measured polarizabilities, and the method of determining the theoretical polarizabilities, are given hereinafter. It should be pointed out that Equation 30 applies, strictly speaking, only when the elements 9 are sufficiently far apart that their mutual effects are negligible. In general, the mutual effects are negligible, substantially, when the spacing between the elements is of the same order of magnitude as the size of the elements. Moreover, while the mutual effects may slightly alter the value of the refractive index, these effects are ordinarily not especially detrimental. If the mutual effects are not negligible, the so-called Clausius-Mosotti Equation 31 given below may be substituted under certain conditions for Equation 30.

$$\frac{n^2-1}{n^2+2}=\frac{N\alpha}{3\epsilon_0} \qquad (31)$$

For the condition of mutual interaction among the elements, Equation 31 is more exact or rigorous than Equation 30, because in Equation 31 the value of the field, acting on and tending to polarise the elements, includes not only the incoming or impressed field $\overline{E}$, but also the local field produced by the surrounding polarized elements. On the other hand, in Equation 30, the value of the field includes only the impressed field $\overline{E}$. In deriving Equation 31 the assumption is made that the elements are arranged in an array having, as in the preferred arrangements of the structures disclosed herein, three-dimensional symmetry.

From Equation 30 we have

$$n=\sqrt{1+\frac{N\alpha}{\epsilon_0}} \qquad (32)$$

Now, for metallic objects or elements, α is positive, as explained hereinafter. Hence the refractive index of the conductive array 10 is greater than unity. Moreover, assuming the medium 8 is air or polystyrene foam, the refractive index of the array 10, taken by itself, is substantially the same as the refractive index of the structure 7, since the dieletric constant of air is unity and therefore negligible, and the dielectric constant of the polystyrene is substantially unity, as explained in my copending applications mentioned above.

Also, since

$$n>1 \qquad (33)$$

v_0 and λ_0 are, respectively, greater than v_1 and λ_1 because, as given in my aforesaid copending applications,

$$n=\frac{v_0}{v_1}=\frac{\lambda_0}{\lambda_1} \qquad (34)$$

where

v_0 and λ_0 are, respectively, the phase velocity and wavelength of the waves in free space, and

v_1 and λ_1 are, respectively, the phase velocity and wavelength of the waves propagated through the medium 8 and the metallic structure 10.

If the dielectric medium 8 is hard rubber, or some similar substance having a dielectric constant ϵ_m substantially different from unity, the overall dielectric constant ϵ_c, of the modified structure, comprising the medium or filler just mentioned and the conductive, array, may be determined from the relation

$$\log \epsilon_c = k_s \log \epsilon + k_m \log \epsilon_m \qquad (35)$$

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 modified structure.

In determining the refractive index of the modified structure comprising a dielectric substance having a dielectric constant substantially different from unity, the value of ϵ_c as determined from Equation 35 should be substituted for the term ϵ appearing in Equation 29.

It is thus apparent that the structure of Figs. 3, 4 and 5 is a delay or artificial dielectric structure for retarding the phase velocity of the waves. As previously stated, the small conductive elements 9 may be regarded as capacitive elements which load free space. Analogously, shunt capacitors on a two-wire transmission line function to reduce the wave velocity. To continue, 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. If metallic elements are inserted, the elements cause rearrangement of the lines of force, and a consequent increase in the number of lines, similar to the rearrangement caused by the shift, mentioned above, of the oppositely charged particles. Hence the conductive elements 9, Fig. 3, 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 non-polar dielectric. Either viewpoint or theory explains satisfactorily the delay action observed in the operation of the metallic structure of Fig. 3, and in the focussing operation of the artificial dielectric lenses to be described herein.

In accordance with Equation 32, the refractive index of the conductive structure 9, Fig. 3, is directly proportional to the number N of elements 9 per unit volume of the structure. Accordingly, the refractive index, and incidentally the capacity and effective dielectric constant, may be increased by staggering the elements 9 preferably, but not necessarily, in a manner such as to preserve the element spacing equal. The staggering should, of course, be such as to prevent short-circuiting of the elements or dipoles. The elements may be staggered only in the vertical plane of propagation 13, or alternatively, they may be staggered obliquely, that is, in both the plane of propagation 14 and the wave front plane 13.

More specifically, considering the embodiment of Figs. 3, 4 and 5, the elements 9 are arranged in six vertical rows 15 in the wave front plane 13, four vertical rows 16 in the propagation plane 14 and five horizontal tiers 17, the corresponding adjacent elements 9, Fig. 4, in each tier being positioned exactly in back of one another. Referring to Fig. 6, which is a side view, corresponding to Fig. 4, of another embodiment, the dielectric medium 8 has the same volume, X, Y and Z, as the medium of Fig. 3. In the propagation plane 14, Fig. 6, the elements 9 in each vertical row 18 are staggered relative to the elements in the two adjacent vertical rows 18, the spacing between the elements 9 being the same as in the embodiment of Fig. 4, whereby the total number of vertical rows 18 spaced in the propagation plane 14, that is, spaced along the depth or thickness dimension Z, is greater than the number of rows 16 in the embodiment of Fig. 4. Accordingly, for the same volume, X, Y, Z, the embodiment of Fig. 6 contains a larger number of elements per unit volume, so that the refractive index of this staggered embodiment is greater than that of the linearly-spaced embodiment of Figs. 3, 4 and 5. In Fig. 5, the dotted elements denoted by reference numerals 19 represent the positions of a few typical staggered elements when staggering only in the propagation plane 14 is utilized; and the dotted lines 20 illustrate the positions of a few typical staggered elements when staggering in both the wave front plane 13 and the propagation plane 14 is employed. In this connection it may be pointed out that the structure of Fig. 3 should be sharply distinguished from the grid structures illustrated by Figs. 3 and 5 of my concurrently filed copending application for "Transmission Systems," Serial No. 748,448, filed on May 16, 1947. In the embodiment of Fig. 3 the element spacing in the horizontal or magnetic (H) plane may be greater than a half wavelength whereby reflection of wave components at the surfaces or faces of the structure does not occur. In the grid structures of my copending application the H-plane spacing is less than a half wavelength so that the horizontal grid strips reflect certain portions of the E components, the unreflected portions of the E components being propagated through the structure only along the spaces between the grid strips.

Inasmuch as the elements 9, Fig. 3, are linear, the structure operates to delay waves having a polarization, or a polarization component, parallel to the vector 11 and a propagation direction having a horizontal component such as direction 12. The elements 9 may, however, have any other configuration or shape and, in particular, they may be spherical or circular and flat, that is, disk-shaped. As stated previously, a structure 10 comprising spherical elements, resembling ball bearings, is truly isotropic since it functions to delay equally waves having any E polarization and any propagation direction incoming to the structure. On the other hand, in a structure comprising metallic disks positioned so that their flat faces extend parallel to the incoming wave front, the optimum delay action is obtained when the incoming wave propagation direction is perpendicular, and the incoming wave front plane is parallel, to the faces of the disks. The disk structure may be considered as quasi-isotropic, since it functions to delay equally all E polarizations in the aforesaid wave front plane.

Referring to Figs. 7, 8 and 9 the polarizability, α_c of a perfectly conducting sphere will now be determined. In Figs. 7 and 9 reference numeral 21 denotes an originally uniform electric field such as that represented by the electric or E vector 11, Fig. 3, and numeral 22 designates a perfectly conducting sphere immersed in the field 21. Now

$$V_a = -Ey = -Er\cos\theta \qquad (36)$$

where

V_a is the potential of the field 21
y is the ordinate parallel to the E vector.

The free charges on the sphere are displaced by the applied field and it thereby becomes an electric dipole having a moment M_c which we wish to determine. In Fig. 7, the electric lines of force enter and pass through the sphere, whereby positive charges appear on one side and negative charges appear on the opposite side, as in Fig. 2, and an electric dipole is simulated. The electric potential, V_{out}, external to or outside the sphere, is the sum of the applied potential, V_a, and the dipole potential, V_d, that is

$$V_{out} = V_a + V_d \qquad (37)$$

and from Equations 9 and 36 we have

$$V_{out} = -Er\cos\theta + \frac{M_c\cos\theta}{4\pi\epsilon_0 r^2} \qquad (38)$$

For the potential V_{in}, inside the sphere, we have

$$V_{in} = 0 \qquad (39)$$

because the sphere 22 is conducting.

As explained on page 73 of the textbook "Electromagnetic Waves" by S. A. Schelkunoff, at a boundary between two dielectrics, there are two requirements, namely,

$$E_{tangential}\text{ (inside)} = E_{tangential}\text{ (outside)} \qquad (40)$$

and

$$\epsilon E_{normal}\text{ (inside)} = \epsilon E_{normal}\text{ (outside)} \qquad (41)$$

Also, as explained on page 19 of the textbook "Static and Dynamic Electricity" by Smythe, the above two requirements may be expressed in terms of the potential as

$$V_{in} = V_{out} \qquad (42)$$

$$\epsilon_{in}\frac{dV_{in}}{dw} = \epsilon_{out}\frac{dV_{out}}{dw} \qquad (43)$$

where

d is the derivative
w is the normal direction to the surface.

But since the conducting element 22 is a sphere,

$r=a$, the radius of the sphere, so that from Equations 38, 39 and 42 we have

$$Ea\cos\theta + \frac{M_c\cos\theta}{4\pi\epsilon_0 a^2} = 0 \qquad (44)$$

or

$$\frac{M_c\cos\theta}{4\pi\epsilon_0 a^2} = Ea\cos\theta \qquad (45)$$

$$M_c = 4\pi\epsilon_0 a^3 E \qquad (46)$$

But, from Equation 23, we have

$$M_c = \alpha_c E \qquad (47)$$

and

$$\alpha_c = 4\pi\epsilon_0 a^3 \qquad (48)$$

Substituting in Equation 30, we may obtain the refractive index of a structure 10, Fig. 3, comprising spherical elements 22. Thus, for a separation S between elements sufficient to render the mutual coupling effects negligible, we have

$$n^2 = \frac{1+4\pi\epsilon_0 Na^3}{\epsilon_0} = \frac{\epsilon}{\epsilon_0} = \epsilon_r \qquad (49)$$

$$n = \sqrt{1+4\pi Na^3} \qquad (50)$$

where

N is the number of spheres per unit volume of the structure, and
n is the refractive index.

In deriving Equations 48 and 50 for a structure comprising perfectly conducting spheres the presence of only an electric field was assumed. In other words the magnetic field, which is inherently coupled to the electric field of an electromagnetic wave was disregarded. Actually, the magnetic field is distorted by the sphere; and this distorted magnetic field tends to reduce the value of the refractive index as given by Equation 50. More particularly, the electric vectors of the super-short wave (microwave) terminate on the conducting sphere, and the electric field is thus perturbed. These electric vectors induce eddy currents on the surface of the conducting sphere which prevent the H or magnetic lines of force from penetrating the surface of the sphere. As a result, the magnetic lines are perturbed and circumvent the sphere. Thus, as shown in Figs. 7 and 9 the electric vectors 11 terminate on the conducting sphere 22 and the electric field is perturbed; and, in addition, as shown in Figs. 8 and 9, the vectors 24 circumvent sphere 22 and the magnetic field 23 is perturbed.

Now, a conductive sphere 22 immersed in a magnetic field 23 is analogous to a dielectric sphere, that is, a theoretical sphere having a zero dielectric constant, immersed in an electric field. The dielectric sphere has an electric dipole moment, M_z, which we shall now determine and which corresponds in a sense to the magnetic dipole moment of the conducting sphere.

Thus, for the dielectric sphere

$$V_{in} \neq 0 \qquad (51)$$

and is unknown, because the sphere is not conducting. But, as stated above, for the dielectric sphere

$$\epsilon_{in} = 0 \qquad (52)$$

and

$$\epsilon_{out} = \epsilon_0 \qquad (53)$$

Accordingly, Equations 38 and 43 may be conveniently utilized to determine M_z. Thus

$$\epsilon_0\frac{d}{dr}\left[-Er\cos\theta + \frac{M_z\cos\theta}{4\pi\epsilon_0 r^2}\right] = 0\Big|_{r=a} \qquad (54)$$

Dividing (54) by

$$\epsilon_0\cos\theta \qquad (55)$$

we have

$$\frac{d}{dr}\left[-Er + \frac{M_z}{4\pi\epsilon_0}\right] = 0 \qquad (56)$$

$$-E\frac{dr}{dr} + \frac{M_z}{4\pi\epsilon_0}\frac{d}{dr}\left[\frac{1}{r^2}\right] = 0 \qquad (57)$$

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but

$$\frac{d}{dr}\left(\frac{1}{r^2}\right)=-\frac{2}{r^3} \qquad (58)$$

so

$$-E+\frac{M_z}{4\pi\epsilon_0}\left[-\frac{2}{r^3}\right]=0 \qquad (59)$$

and since

$$r=a \qquad (60)$$

we have

$$-E-\frac{M_z}{2\pi\epsilon_0 a^3}=0 \qquad (61)$$

or

$$M_z=-2\pi\epsilon_0 a^3 E \qquad (62)$$

Hence, from Equations (23) and (62) we have

$$\alpha_z=-2\pi a^3 \qquad (63)$$

As shown by Equation 63, the electric polarizability α_z of a sphere having a zero dielectric constant is negative and equal to one-half the value of the polarizability α_c of the conducting sphere, as given by Equation 48. Similarly, at superhigh frequencies, the conducting sphere possesses a negative magnetic polarizability and the effective permeability of the medium comprising conducting spheres will be altered.

To recapitulate, for the conductive sphere, the inside potential V_{in} is zero and the inside dielectric constant ϵ_{in} is not zero, so that Equation 42 rather than Equation 43 was utilized in conjunction with Equation 38 in determining its polarizability α_c. On the other hand, for the dielectric sphere, the inside potential V_{in} is not zero and the inside dielectric constant ϵ_{in} is zero, so that Equation 43 rather than Equation 42 is employed in conjunction with Equation 38 in ascertaining its polarizability α_z.

The equation for the relative permeability, μ_r, of a conducting element is similar to Equation 30 for the relative dielectric constant, ϵ_r, of the element, that is,

$$\mu_r=1+N\frac{\alpha_\mu}{\mu_0} \qquad (64)$$

μ_r is the relative permeability
μ_0 is the permeability in free space
α_μ is the magnetic polarizability.

For a spherical element, we have

$$\mu_r=1-2\pi Na^3 \qquad (65)$$

which is analogous to Equation 49.

Now, from Equations 30, 34, 50 and 65 we have for the conducting sphere

$$n=\frac{v_0}{v_1}=\sqrt{\mu_r\epsilon_r} \qquad (66)$$

$$=\sqrt{(1-2\pi Na^3)(1+4\pi Na^3)} \qquad (67)$$

$$=\sqrt{1+2\pi Na^3} \qquad (68)$$

It should be observed that the value of the refractive index Equation 68, for a structure comprising conducting spheres, as obtained when the magnetic field 23 is not disregarded, is smaller than the value obtained in Equation 50; when the magnetic field is disregarded. Hence, if the frequencies are sufficiently low so that eddy currents do not form on the sphere, Equation 50 for the refractive index is applicable, whereas if the frequencies utilized are relatively high, so that eddy currents are produced, equation 68 is applicable.

It may be interpolated here that the focussing action of the fast, metallic-advance, lens comprising dielectric channels and disclosed in my copending application mentioned above, Serial No. 642,723, filed January 22, 1946, may be attributed to polarization effects. In the fast channel lens, the electric lines of force entering the channels are forced to assume the sinusoidal distribution in accordance with the dominant mode. Hence these lines of force are perturbed by the metallic walls in substantially the same manner as they would be perturbed by spheres each having a zero dielectric constant. The polarizability is negative so that

$$\epsilon_r=1+\frac{N(-\alpha)}{\epsilon_0} \qquad (69)$$

$$=1-K \qquad (70)$$

now, if

$$k=\left(\frac{\lambda}{2q}\right)^2 \qquad (71)$$

where

q is the H-plane or "a" dimension of the dielectric channel

and if

$$q>\frac{\lambda}{2} \qquad (72)$$

we have

$$\epsilon_r=1-\left(\frac{\lambda}{2\lambda}\right)^2 \qquad (73)$$

and

$$n=\sqrt{\epsilon_r}=\sqrt{1-\left(\frac{\lambda}{2q}\right)^2} \qquad (74)$$

which corresponds to the equation for the refractive index, as given in the copending application just mentioned.

As previously discussed, the magnetic field perturbance, produced at high frequencies by the eddy current effect, may be substantially eliminated by shaping the elements so that the magnetic lines are not perturbed. More specifically, each element may be shaped so as to have a negligible small dimension in the direction of the wave propagation and, in the direction of the electric field, the same dimension as in the sphere. Thus, referring to Fig. 9, reference numeral 25 denotes a conducting circular disk having its flat faces parallel to the E vector 11 and the H vector 24. Now the torque, T, on a flat disk having a radius, R may be expressed as

$$T=\left[\frac{16R^3\epsilon_0}{3}(E\sin\theta)\right][E\cos\theta] \qquad (75)$$

where R is the radius of the disk.

The first bracket represents the dipole moment, the second field: and the product is the torque. For the disk 25 having its plane or face parallel to E

$$\sin\theta=1 \qquad (76)$$

and since, as given by Equation 23,

$$\overline{m}=\alpha\overline{E} \qquad (77)$$

we have

$$\alpha_{disk}=\frac{16\epsilon_0 R^3}{3} \qquad (78)$$

where α_{disk} is the electric polarizability of the disk. Hence, from Equation 30, neglecting mutual effects, we have

$$n=1+\frac{16}{3}NR^3=\epsilon_r \qquad (79)$$

The refractive index, n, for the array of disks, as given by Equation 79 is independent of the magnetic field, as already indicated.

Referring to Figs. 10 and 11, reference numerals 26 denote forty-seven conductive spherical elements resembling marbles, or pellets, and mounted on vertical wooden dowels or rungs 27, the rungs 27 being supported by the wooden base member 28. The pellets are dispersed or spaced along the three axes or directions, X, Y, and Z in the air dielectric medium 29 and in a manner such as to form an electromagnetic delay array 30. More particularly, the medium 29 and the array 30 together constitute a delay structure or prism 31 having a front face 33 and an inclined back face 33. The pellets 26 are grouped in three vertical panels, namely, a front panel 34 comprising twenty-five pellets, an intermediate panel 35 comprising twelve pellets and a back panel 36 comprising ten pellets. The front panel 34 comprises five horizontal tiers 37 each having five pellets, the middle panel comprises three horizontal tiers 38 each having four pellets and the back panel 36 comprises two horizontal tiers 39 each having five pellets. Considered differently, the front panel 34 comprises five verticals or stacks 40 each having five pellets, the middle panel 35 comprises four vertical stacks 41 each having three pellets and the back panel 36 comprises five stacks 42 each having two pellets. As is apparent from the drawing, the front and back panels 34, 36 are aligned; and the intermediate panel 35 is obliquely, that is, vertically and horizontally, staggered relative to the two outer panels 34, 36. Thus, as shown by the dotted lines 43, Fig. 10, the corresponding stacks 40, 42 in the front and back panels 34, 36 are horizontally aligned and, as shown by the dotted lines 44, Fig. 11, the two tiers 39 of the back panel 36 are aligned with the two bottom tiers 38 of the front panel 34, whereby each pellet 26 in the back panel 36 occupies a position in the medium 29 corresponding, in the vertical and horizontal planes, to that occupied by a pellet in the front panel 34. Each tier 38, Fig. 11, of the middle panel 35, is positioned mid-way between two adjacent tiers 37 of the front panel 34; and each stack 41 of the middle panel 35 is positioned mid-way between the lines 43 connecting the corresponding stacks 40, 42 of the front and back panels 34, 35. The center-to-center spacings, S, between each pellet and the pellets adjacent thereto are substantially equal.

As explained above, the electric polarizability α of each sphere or pellet is directly proportional to the cube of the radius of the pellet and, assuming the radius a is given and the mutual effects are negligible, α may be ascertained from Equation 50 or 62. With α determined and the desired index of refraction n selected, n being greater than unity as, for example, 1.36, the number N of pellets per unit volume of the prism and hence the center-to-center spacing S for the pellets of known radius a may be ascertained. Conversely, with a and N, and therefore S, selected, the theoretical value of n may be ascertained. In this connection it should be noted that, while the total number of pellets in the prism of Figs. 10 and 11 is forty-seven, the prism may contain a different number of pellets, and the prism may have any practical total volume. Moreover, the number of pellets in each panel, or tier, or in each stack, may of course be considerably different from the number illustrated, provided that the desired optical configuration for the structure is preserved. By way of illustration, assuming the diameter of each pellet is three-eighths of an inch and the center-to-center spacing S is equal to three-quarters of an inch, N equals about 2.38. Also, while the dielectric medium is air, the medium may of course be any other dielectric substance. Again, if desired, the entire structure may be enclosed in an evacuated container, and the medium may be the enclosed vacuum.

In operation, Figs. 10 and 11, waves having a propagation direction 12 and an electric polarization 11, or any other polarization in the plane of the wave front 13 are propagated through the prism 31 and, since the refractive index is greater than unity, the phase velocities of the wave components passing through the thicker portion of the prism are delayed a greater amount than the phase velocities of the components passing through the thinner portion, with the result that the propagation direction of the wave front is bent toward the thicker portion, as in an optical lens, and the emerging outgoing direction 45 is at an angle to the incoming direction 12.

Referring to Figs. 12 and 13, reference numeral 30 designates a metallic delay array, or artificial dielectric material, which comprises, as in the array 30 of Fig. 10, conductive pellets 26 dispersed along the X, Y and Z axes in the air dielectric medium 29. The array 30 comprises fifty pellets and is shaped so as to form a plano-convex circularly symmetrical delay lens 50 having a front flat face 51 and a back convex face 52, an optical axis 53 and a point focus 54. The refractive index, n, of the lens 50 is greater than unity and may be determined in the manner explained above in connection with the prism 31. For example, the index of the lens 50 may be the same as that of the prism 31. Numeral 55 denotes a point type primary antenna, such as a conical horn, having its orifice coincident with the point focus 54 of the lens. The horn is connected by a dielectric guide 56 to a radio translation device 57, such as a microwave transmitter, receiver or radar transceiver.

More specifically, the pellets of the lens 50 are grouped in three panels 34, 35 and 36, the front, middle and back panels 34, 35 and 36 comprising respectively, twenty-five, sixteen and nine pellets. The front panel 34 is the same as the front panel 34 of the prism 31, Fig. 10, and comprises five tiers 37 of five pellets each, or five stacks 40 of five pellets each. The middle panels 35 of the lens 50 comprises four tiers 38 of four pellets each, or four stacks 41 of four pellets each. The back panel 36 comprises three tiers 39 of three pellets each or three stacks 42 of three pellets each. Since the lens 50 is not of solid construction the faces 51 and 52, shown in dot-dash lines, are not physical surfaces but are in a sense, optical surfaces. Also, while the diameter or aperture 58 of the lens 50 is such that the front and back faces 51, 52 do not intersect any of the pellets, the aperture 58 may be smaller than shown and such that the corresponding convex face, illustrated by the dotted line 59, and one or more outer pellets intersect, so that a portion of each intersected pellet lies outside the lens and the remaining portion is included in the lens. In this event, the pellet portions external to the lens should be removed, in order to secure the desired optical contour. In other words, the lens may comprise only whole pellets, or both whole and fractional pellets.

The equation for the convex contour of the back face 52 will now be determined. In Fig. 13,

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the reference letter A denotes the phase length of the path traversed by a wavelet or ray emitted at the focus 54 and propagated through the thick vertex portion of the lens and along the lens axis 53 to the flat front face 51. Reference letter B denotes the phase length of the path traversed by a ray emanating from the focus 54 and propagated to the periphery so as to just avoid the lens and reach the front face 51. In order to convert the spherical wave front 60 originating at the focus 54 into a plane wave front 61 at the front face 51, A and B must be equal.

Now

$$A=\frac{f}{v_0}+\frac{x}{v} \tag{80}$$

and

$$B=\frac{\sqrt{(f+x)^2+y^2}}{v_0} \tag{81}$$

where

f is the focal length of the lens,
x is the lens thickness along the axis 53,
y is the radius or half-aperture of the lens,
v is the phase velocity in the lens, as before, and
v_0 is the phase velocity in free space.
Hence,

$$\frac{f}{v_0}+\frac{x}{v}=\frac{\sqrt{(f+x)^2+y^2}}{v_0} \tag{82}$$

or, since

$$n=\frac{v_0}{v} \tag{83}$$

where n is the refractive index we have

$$(n^2-1)x^2+2fx(n-1)-y^2=0 \tag{84}$$

which is the equation for a hyperbola.

In operation, Figs. 12 and 13, assuming the device 57 is a transmitter, energy is supplied by the transmitter 57 over guide 56 to the horn 55 and a wave having a polarization 11 and a spherical wave front is propagated towards the lens 50. The phase of the wave components passing through the thick central of 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 front face 51 are cophasal. Stated differently, an outgoing spherical wave front 60 is converted by the lens to a plane front 61 extending perpendicular to the axis 53. In reception, the converse operation is obtained, and an incoming plane wave 61 having a propagation direction parallel to the axis 53 is transformed by the positive hyperbolic-plano lens into a spherical wave front 60 converging on the focus 54. In other words, the incoming parallel rays 62, 63 are bent or refracted by the lens, as illustrated by the rays 64, 65 and focussed on the primary antenna 55. Inasmuch as the lens 50 is circularly symmetrical, focussing action is obtained in all planes containing the optical axis 53. Also, since the elements 26 are spherical the lens 50 is isotropic. In practice, a lens constructed in accordance with Figs. 12 and 13 and comprising pellets having diameters of three-eighths of an inch and spaced center-to-center three-quarters of an inch operated in a highly satisfactory manner.

The plano-convex lens 70 of Figs. 14 and 15 is the same as the lens 50 of Figs. 12 and 13 except that polystyrene foam having a dielectric constant of 1.014, that is, substantially unity, and a refractive index of 1.007, also substantially unity, is utilized in place of air as the dielectric medium. In Figs. 14 and 15, reference numerals 71, 72 and 73 denote three thick polystyrene foam slabs in which the pellets 26 of panels 34, 35 and 36 are embedded, respectively. Numerals 74 and 75 denote two thin polystyrene foam spacer sheets included, respectively, between slabs 71 and 72 and slabs 72 and 73. The panels 34, 35 and 36 constituting the metallic delay lens 70 are substantially the same as the panels 34, 35 and 36 of the lens 50. The operation of the system of Figs. 14 and 15 is substantially the same as that of Figs. 12 and 13. In one embodiment of the invention, constructed in accordance with Figs. 14 and 15 and successfully tested, the pellets 26 were three-eighths of an inch in diameter and spaced center-to-center three-quarters of an inch.

Referring to Figs. 16, 17 and 18, reference numeral 80 denotes a quasi-isotropic, circularly symmetrical, delay lens comprising a dielectric medium 81 having a dielectric constant of unity, substantially, and a metallic delay array 82 immersed therein. The dielectric medium 81 comprises five closely adjacent circular slabs 83, 84, 85, 86 and 87 of polystyrene foam and the negligible air dielectric 88 between the adjacent parallel slabs. Numerals 89, 90, 91, 92 and 93 denote the front surfaces, and numerals 94, 95, 96, 97 and 98 designate the back surfaces, of the slabs 83, 84, 85, 86 and 87, respectively. The slabs are coaxially supported on the wooden cross-member or rung 99, the wooden uprights 100 and the wooden base member 28. The metallic delay array 82 comprises a large number of copper foil disks 101 having negligible thickness and mounted on the back surfaces of the five slabs, and on the front surface of slab 83, in a manner such that the conductive disks are uniformly dispersed along three dimensions in the medium 81. Hence the front and back faces, and the diametral dimension of each disk 101, extend parallel to the wave front 13 which contains the electric vector 11. Considered differently, the metallic delay structure comprises six circular metallic panels 102, 103, 104, 105, 106 and 107 spaced equally along the optical axis 53 of the lens 80 and comprising different pluralities of metallic disks 101. Each panel contains whole and fractional disks. The disks 101 in panels 103, 105 and 107 are obliquely staggered relative to the disks 101 in panels 102, 104, and 106. Numerals 108 denote polystyrene foam spacers mounted on the rung 99 between the slabs and adjacent the outer slabs, and preferably dimensioned so that the center-to-center spacings S of the adjacent disks in the adjacent panels and the center-to-center spacings S of the adjacent disks in each panel are equal. If desired, the spacers 108 may be omitted and the slabs 83 to 87 may each have a thickness such as to render the slabs contiguous, whereby the air spacing between slabs is eliminated, substantially. The diameters of the slabs, and hence of the panels, are progressively stepped in conformity with the plano-convex shape of the lens.

As already discussed, the electric polarizability a_{disk} of each disk 101 is directly proportional to the cube of the radius R of the disk and, assuming the radius is given, may be ascertained from Equation 78. With a_{disk} determined and both the radius R and the desired index of refraction n selected, the number N of disks per unit volume of the metallic lens 80, and hence the center-to-center spacing, S, of the disks may be determined from Equation 79, assuming mutual effects are disregarded, or from Equations 31 and 78 if the mutual effects are considered. Conversely, with R and N, and therefore S, selected, the theoretical value of n may be ascertained. The operation of the disk lens of Figs. 16, 17 and 18 is essentially the same as that of the lens of Fig. 12 or Fig. 14. The lens 80 is, however, isotropic only for waves having a propagation direction parallel to the axis 53 whereas, as stated above, the lens 50 and the lens 70 are each truly isotropic. As in the lenses 50 and 70, focussing obtains in all axial planes of the lens 80 and a pencil or point type beam is produced.

As shown by Fig. 19, in which reference numeral 110 denotes the measured E-plane directive pattern for an antenna system constructed in accordance with Figs. 16, 17 and 18, the directive action of the small delay lens 80 is highly satisfactory. In the tested system just mentioned, the lens diameter or aperture, the disk radius R and the disk spacing S were, respectively twenty-four inches, five-sixteenths of an inch, and one inch; and the pattern was measured at a design wavelength of λ equal to 7.25 centimeters. The pattern 110 comprises a single major lobe 111, the two vestigial lobes 112 and the minor lobes 113. As is desired, the vestigial and minor lobes are considerably below the peak of the major lobe, the vestigial lobes being 15 decibels and the minor lobes being 20–25 decibels down from the peak. The relative intensity of the minor lobes is, in general, more satisfactory than obtained in prior art reflective antenna structures. The half-power width 114 of the major lobe is 7.6 degrees. This beam or lobe width is dependent upon several factors including the focussing action of the lens, and it is also directly proportional to the lens aperture. The 7.6 degrees beam width for the lens of the invention is comparable to the beam widths of other prior art passive antenna members, such as parabolic reflectors, zone plate and other lenses, having two-foot apertures. It may be observed that, as disclosed in my companion application, a polarized metallic delay strip lens having a six-foot aperture has a half-power beam width of only 2.68 degrees. Hence, the beam width of a lens constructed in accordance with Figs. 16, 17 and 18 and having a six-foot aperture would be about 2.68 degrees.

In practice, the panels of the lens 80 are constructed by individually applying or mounting the copper foil or aluminum disks on the polystyrene slabs. A delay lens of the disk type may, however, be more easily and simply constructed by spraying conductive material, such as paint, on one side of each of many thin solid dielectric sheets through a thin sheet-metal master plate perforated with small round or square holes of proper size. A circular mask is interposed, during the spraying process, between the plate and the sheet in order to obtain a circular panel of spaced conductive dots or "motes." The size or diameters of the various masks are graded in a manner such that the desired convex lens contour is secured when the sheets are stacked or assembled to form the delay structure. In the assembled lens the sheets are bolted together and solid dielectric or wooden spacers may or may not be inserted between the adjacent sheets, dependent upon the thickness of the sheets, for securing the proper spacing of elements in a direction parallel to the optical axis of the lens.

Figs. 20, 21, 22 and 23 illustrate a painted disk or dot lens constructed as just described. In more detail, reference numeral 120 designates a quasi-isotropic, circularly symmetrical, delay lens comprising four solid dielectric spacer sheets 123, 125, 127 and 129 and five solid dielectric panel sheets 122, 124, 126, 128 and 130. Reference numerals 132, 133, 134, 135 and 136 denote circular panels painted on the panel sheets 122, 124, 126, 128 and 130, respectively, and having graded diameters tapering from a maximum for panel 132 to a minimum for panel 136 in conformity with the convex hyperbolic optical face 52 of the lens 120. The panels comprise different pluralities of square dotes or motes 137 of conductive paint, and are not staggered. The adjacent motes 137 of each panel are spaced a distance S; and the thicknesses of the panel and spacer sheets are selected such that the corresponding motes in adjacent panels are spaced a distance S. The panel and spacer sheets, assembled as shown in Fig. 20, are held securely together by the wooden frame members 121 and the nut and bolt assemblies 131. The panel and spacer sheets may be composed of polystyrene foam or other suitable dielectric material such as cellophane. If the material is transparent, the motes 137 produce a shading effect, as shown in Fig. 21, which decreases in all radial directions from a maximum intensity at the center of the lens to a minimum at the periphery, by reason of the circular symmetry of the lens.

The electric polarizability α of the individual square mote having a side length 2R is not substantially different from the polarizability α of a circular mote having a radius R. Hence with the side half-length R (or radius R) given, the polarizability α may be ascertained from Equation 78, as in the lens 80 of Fig. 16. With α determined and R known, the desired refractive index n greater than unity may be obtained by properly selecting N and S in accordance with Equation 79. The quasi-optical and electrical operation of the system of Fig. 20 is substantially the same as that of the system of Fig. 16.

Referring to Figs. 24 and 25, the metallic delay painted disk lens 140 is substantially the same as the painted lens 120 of Figs. 20, 21, 22 and 23, except that the lens 140 is cylindrically symmetrical and has a line focus 141, whereas the lens 120 is circularly symmetrical and has a point focus 54. The front face 51 of the lens 140 is cylindrically convex and the back face 52 is flat. The lens 140, Figs. 24 and 25, comprises five polystyrene foam rectangular slabs 142, 143, 144, 145 and 146 and the five conductive panels 147, 148, 149, 150 and 151, sprayed on the aforesaid slabs, respectively. The panels are not staggered and they have equal lengths but graded widths. As in the lens of Fig. 20, the motes 137 are of conductive paint. The slab thicknesses are such that the spacings S between adjacent motes 137 and along the three dimensions X, Y and Z of the structure, are equal. Numeral 152 denotes a sectoral horn connected to guide 56 and device 57 and having its long mouth aperture 153 aligned with the focal lens 141 of the lens 140.

The mote polarizability α, the mote side half-length R, the number N of motes per unit volume of the structure, the spacing S between motes and the refractive index n are the same as in the lens of Fig. 20. In operation, the sectoral horn energizes the focal line 141 and the lens delays the inner rays passing through the thicker lens portion relative to the outer rays. Hence the

EXAMINER

cylindrical wave front emerging from the horn mouth aperture 153 and aligned with the line focus 141 is transformed by the lens 140 to a plane wave. In other words, the lens focusses the waves in the E or vertical plane containing the electric polarization 11 but does not focus in the H or horizontal plane. Accordingly, a fan beam is produced having a small width in the E-plane and a large width in the H-plane. If desired, a point beam may be secured by properly inserting a lens in the horn mouth aperture 153, as is well known.

As already stated, the "E" dimension, that is, the dimension as measured in a direction parallel to the electric wave polarization, of each conductive element in the structures described thus far is relatively small compared to a half wavelength, and therefore such as to avoid resonant effects. Moreover, the structures illustrated by Figs. 3, 10, 12, 14, 16, 20 and 24 have a relatively broad band with, since the frequency bands or regions in which they are ordinarily used are sufficiently remote, from the region of anomalous dispersion, that the effective dielectric constant and the refractive index do not vary appreciably with frequency. To illustrate, in a tested system comprising elements having an E dimension corresponding to a quarter wavelength at $\lambda=$ to 7.6 centimeters (3,947.3 megacycles) the index of refraction n varied from 1.41 at $\lambda=8$ centimeters (3,750 megacycles) to 1.43 for $\lambda=7$ centimeters (4,285.7 megacycles). In other words, the index n increased only 0.02 as the wavelength decreased one centimeter, that is, as the frequency increased 535.7 megacycles. As the frequency increases from 4,285.7 megacycles, the index n increases until at

$$\lambda=\frac{7.6}{2}=3.8$$

centimeters corresponding to 7,894.6 megacycles the metallic structure is opaque and the index n is very high. At this wavelength the E dimension of the elements is a half wavelength, whereby resonant effects occur and the artificial dielectric or metallic structure acts like an ordinary solid dielectric substance near its region of anomalous dispersion. At the lower wavelengths, that is, higher frequencies, the metallic structure appears to have an index of refraction less than unity. With the index n less than unity, the phase velocity of the waves propagated therethrough is accelerated rather than retarded, and the refractor becomes a fast metallic advance refractor. To continue, linear elements or rods positioned parallel to the E vector and having an E dimension or length of a half wavelength have a very broad resonance band, and the region or range of anomalous dispersion in a metallic artificial dielectric structure comprising such rods is very large. This region, or frequency band, may be considerably reduced by tilting the half wave rods in the wave front plane, so that they are more nearly perpendicular to the electric (E) vector, whereby the rods become loosely coupled to the moving field and acquire a higher "Q." The rods should be unsymmetrically or dissimilarly tilted in order to insure a rapid decrease in the radiation damping, and hence a sharp resonant characteristic, and to minimize radiation from the array of rods. Symmetrically tilting the rods would result in maximum radiation from the array of a wave polarized parallel to the rods.

Referring now to Figs. 26, 27 and 28, reference numeral 160 denotes a frequency-sensitive metallic artificial dielectric structure comprising a plurality of resonant aluminum rods 161 each a half wavelength long at a given frequency and disposed in four vertical panels 162, 163, 164 and 165. Considered differently, the rods 161 are arranged in ten horizontal tiers 166. The adjacent rods 161 in each panel are oppositely tilted. The corresponding rods 161 in each tier are embedded in the same polystyrene foam horizontal slab 167, as illustrated, the thickness or vertical height of each slab being approximately the same as the vertical projection "L_v" of the rod length "L." Numerals 168 denote polystyrene spacer slabs each of which is positioned between a different pair of adjacent tier slabs 167. As shown in more detail in Fig. 27, the rod tilt is such that the center-to-center horizontal spacing S_x of the rods is about three times the vertical center-to-center spacing S_y of the rods, and the horizontal rod spacing S_z is about one half the horizontal S_x spacing, the spacings S_y being preferably less than one quarter of the aforesaid given wavelength. As shown by Fig. 28, assuming the structure 160 is used as a lens, the front face 169 of the structure 160 is circular and flat. The back face is circularly convex or circularly concave, as shown by the dot-dash lines 170 and 171, Fig. 26, dependent upon the operating frequency of the translation device 172. The device 172 includes means for varying the operating frequency or is designed so that the frequency may be easily altered.

In operation, Fig. 26, assuming the operating frequency of device 172 is higher than any of the frequencies included in the anomalous dispersion region for the structure 160, the dielectric constant and refractive index of the structure are each less than unity and the phase velocity, v, of the waves in the lens 160 is greater than the phase velocity, v_0, of free space. Accordingly, the back face of the lens 160 is made ellipsoidally concave, in accordance with the disclosure in my aforesaid copending application Serial No. 642,723. On the other hand, if the frequency of device 172 is lower than any of the frequencies in the anomalous dispersion region, the dielectric constant and refractive index of the structure are each greater than unity and the phase velocity, v, of the waves in the lens 160 is smaller than the free space phase velocity, v_0. Accordingly, in this case, the back face is hyperbolically convex, as in the structure illustrated, for example, by Fig. 13. In either case the lens 160 functions to focus the waves in all planes containing the lens axis 53, as already explained.

Referring to Fig. 29, reference number 173 denotes a measured dispersion curve of a metallic structure constructed in accordance with Figs. 26, 27 and 28 and in which L, L_v, S_x, S_y and S_z were respectively 1.25 inches, 0.25 inch, 1.5 inches, 0.5 inch and 0.75 inch. In the test, the operating wavelength was 7.6 centimeters. As shown by curve 173 the region of anomalous dispersion for the tested metallic structure 160 occurs when the rods 161 are approximately a half wavelength long. In other words, the curve shows that the structure is resonant at a frequency of about 3,947 megacycles, and at this frequency the 1.25 inch, or 3.175 centimeter, rods are almost a half wavelength long since 3,947 megacycles correspond to 7.60 centimeters. Thus, it is seen that the structure 160 has an anomalous dispersion region analogous to that of a solid dielectric refractor. Because of the rapid change of the refractive index n with frequency, the artificial dielectric 160 may be utilized, in prisms or variable focal length lenses, as a means for separating narrow channels. Also, as will be disclosed and claimed in my last-mentioned proposed application, if desired, a slow lens in accordance with Fig. 16, for example, may be combined with the fast dielectric channel lens of my copending application, Serial No. 642,723, to secure a compound achromatic metallic fast-slow lens.

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 plano-convex metallic lens for refracting a radio wave comprising flat circular conductive disks mounted on solid dielectric members and spaced along three directions in said lens, the flat faces of said disks being parallel to the electric polarization of said wave, said disks having equal diameters each less than one-half of the wavelength of said wave.

2. A plano-convex, circularly symmetrical, lens for refracting a radio wave having a given wavelength, said lens comprising circular polystyrene foam slabs extending parallel to each other, a plurality of metallic disks mounted on each slab, the spacing between adjacent slabs and between adjacent disks on the same slab being less than the wavelength of said wave and the diameter of each disk being less than one-half of said wavelength.

3. A device for refracting electromagnetic waves, the wavelength of which is within a predetermined range of wavelengths, said device comprising a plurality of arrays of conductive elements said elements being substantially alike and having a maximum dimension which is small with respect to the wavelength of the median frequency of said range of wavelengths, each of said arrays comprising a plurality of said conductive elements substantially uniformly distributed over the entire surface of a plane area, the major dimensions of said area being large with respect to said maximum element dimension, the spacings between adjacent elements not exceeding three times the said maximum dimen-

sion of said elements, said plurality of arrays being placed with their respective planes parallel to each other along a common axis perpendicular to said planes, the spacings between the planes of adjacent arrays being substantially the same as the inter-element spacings of the arrays.

4. The device of claim 3 in which contour lines defined by the outermost edges of the outermost elements of the plurality of arrays of elements are substantially those of a plano-convex lens.

5. The device of claim 3 in which the conducting elements are circular disks.

6. The device of claim 3 in which the conducting elements are spheres.

7. The device of claim 3 in which the conducting elements are short pieces of rod.

8. The device of claim 3 in which the contour lines defined by the outermost edges of the outermost elements of the plurality of arrays of elements are those of a simple type of optical refractor.

WINSTON E. KOCK.

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