Feb. 11, 1969 R. L. HORST 557,025 3,427,627

STACKED DIELECTRIC DISC LENS HAVING DIFFERING RADIAL DIELECTRIC GRADATIONS

Filed June 13, 1966

FIG. 1.

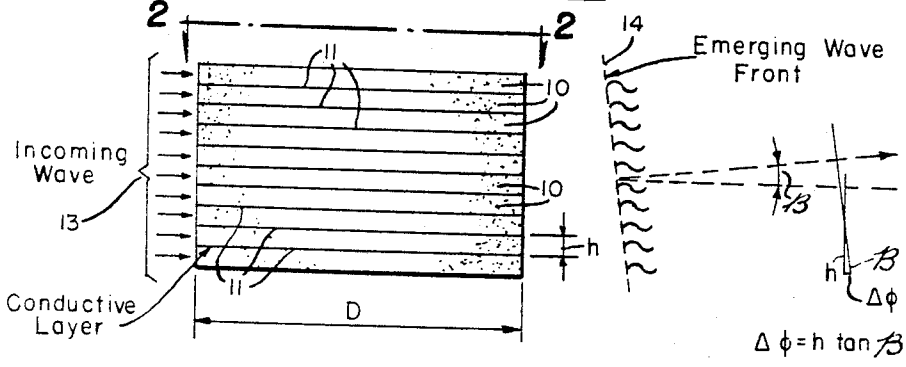


FIG. 2.

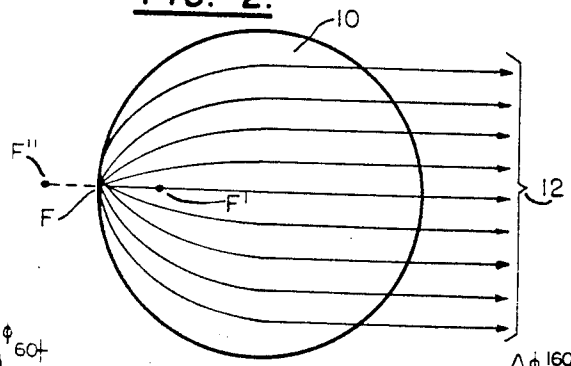
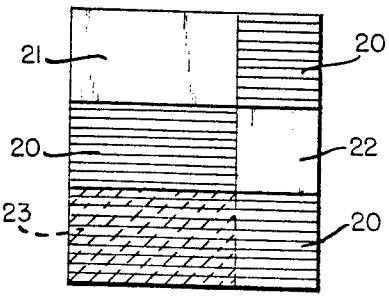


FIG. 3.



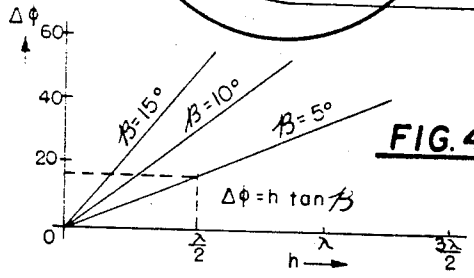


FIG. 4A.

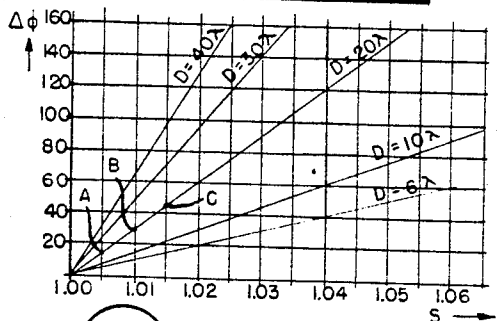


FIG. 4B.

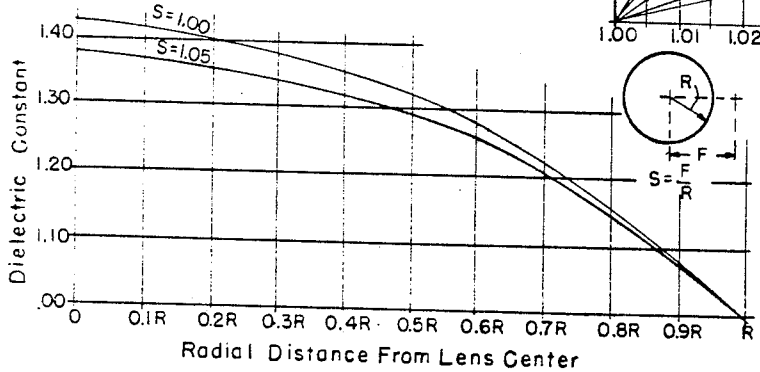


FIG. 5.

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United States Patent Office 3,427,627 Patented Feb. 11, 1969

3,427,627

STACKED DIELECTRIC DISC LENS HAVING DIFFERING RADIAL DIELECTRIC GRADATIONS

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Filed June 13, 1966, Ser. No. 557,025
U.S. Cl. 343—911 9 Claims
Int. Cl. H01q 15/08

ABSTRACT OF THE DISCLOSURE

A plurality of stacked dielectric discs are separated from one another by intervening conductive layers. The discs have differing radial dielectric gradations provding a progressive change in effective electrical length to energy passing through the discs between said conductive layers.

The present invention relates to improved lens and reflector structures for use at high radio frequencies, particularly at frequencies in the microwave portion of the spectrum; and is more particularly concerned with such structures wherein the lens or reflector comprises a combination of variably graded dielectric sections associated with cooperating conductive materials, all so arranged as to produce a lens array operating to convert an incoming plane wave into an emerging plane wave which has a wave front disposed at a desired angle to the wave front of the incoming wave.

Various forms of microwave lens and reflector structures, including those employing masses of dielectric material, have been suggested heretofore. For the most part, these prior structures are adapted to receive microwave energy, and are designed to refract or reflect such energy to produce an emerging wave having a wave front generally parallel to that of the incoming wave (or of the energy source). In some applications, however, it is desirable to achieve an emerging beam angle which "looks above the horizon" in response to incidence of a wave having a vertical wave front (or directed generally parallel to the horizon); and, in its broader aspects, it is sometimes desirable to achieve a predictable angle between the incident and emerging wave fronts associated with a microwave lens or reflector. The present invention relates to a structure adapted to effect this desirable result with relatively high efficiency, and in a construction which is far simpler in configuration and less expensive to manufacture, install, and maintain, than has been the case with lens arrays suggested heretofore.

It is accordingly an object of the present invention to provide an improved array of microwave refractive materials, adapted for use as a lens or reflector, and arranged to achieve a predictable variation in beam angle between incoming and emerging wave fronts associated with said array.

Another object of the present invention resides in the provision of a dielectric lens or lens reflector structure which is simpler and less expensive to fabricate and utilize, which achieves a desired variation in beam angle, and which has a higher efficiency of operation for a given size than has been the case heretofore.

A further object of the present invention resides in the provision of an improved lens or lens reflector structure comprising a plurality of two dimensionally graded lens sections, associated with appropriate conductive structures, all so arranged as to achieve a desired variation in beam angle.

A still further object of the present invention resides in the provision of a novel technique for designing and fabricating an array of focused and slightly defocused

microwave lens sections cooperating with one another to convert an incoming wave front into an emerging wave front which is angled to said incoming wave front.

In providing for the foregoing objects and advantages, the present invention contemplates the provision of a microwave lens or lens reflector structure taking the form of a plurality of two dimensionally graded lenses (e.g. a plurality of cylindrical lenses having Luneberg and modified Luneberg gradations) stacked upon one another, so as to produce a generally cylindrical structure adapted to refract microwave energy. The individual stacked lens sections are so graded dielectrically as to exhibit successively greater electrical lengths, or so as to provide successively longer delays to incident energy; and the several stacked lens sections, so graded, are separated from one another by metal or conductive interfaces such as aluminum foil layers to assure that each lens section operates independently of the other sections. The resulting arrangement may thus be treated as an array of focused and slightly defocused lenses arranged in a unitary configuration; or, in the alternative, it may be treated as an array of the type described wherein the various different lens sections, stacked one upon the other, exhibit successively different electrical lengths or successively different delays to incident energy. The resultant structure thus causes a phase delay from one section to the next adjacent section with regard to the emerging wave, with the result that the emerging wave front is angled with respect to the wave front of incident energy. The structure thus operates to produce what might be termed "squint" i.e. the array tends to look above the horizon in response to incident energy which is directed generally parallel to the horizon.

The lens array can be used as a lens structure, as will appear hereinafter. In the alternative, the stacked array of dielectric lenses can be associated with curved reflector strip means extending along the outer peripheral surface of the cylindrical lens mass in directions concentric with the central axis of said cylindrical mass, so as to operate as a lens reflector adapted to receive incident energy and to reflect that energy into a wave front which emerges from the structure at an angle to that of the incident energy. The disposition of peripheral reflective surfaces can take the form described in my prior co-pending application Ser. No. 533,473, filed Mar. 11, 1966, now U.S. Patent No. 3,307,187 for "Omniazimuthal Reflectors"

The foregoing objects, advantages, construction, and operation of the present invention will become more readily apparent from the following description and accompanying drawings in which:

FIGURE 1 is a side view of a lens structure constructed in accordance with the present invention, and includes diagrammatic representations indicative of the lens operation;

FIGURE 2 is a plan view of the structure shown in FIGURE 1;

FIGURE 3 is a side view of a lens reflector constructed in accordance with one embodiment of the present invention;

FIGURES 4A and 4B are graphs of various parameters useful in designing the structures of FIGURES 1, 2, and 3; and,

FIGURE 5 is another graphical representation of various parameters useful in designing structures constructed in accordance with the present invention.

Referring initially to FIGURES 1 and 2, it will first be noted that the lens or lens reflector structure of the present invention, comprises a plurality of two-dimensionally graded dielectric lenses **10**, stacked upon one another, and separated from one another by metal or conductive interfaces **11**, consisting of foil, conductive paint, or the like. The provision of the interfaces **11** tends to

assure that each of the lenses **10** operates independently of the other lenses **10** in the overall array.

The individual lenses **10** are essentially of wafer configuration, and may exhibit a height *h* of, for example, one-half wavelength and a diameter D greater than approximately 3 wavelengths (i.e. at an operating frequency of 10 gigacycles, *h* would be 1½ centimeters and D would be greater than 9 centimeters). Each of these lens wafers **10** exhibits a two-dimensional radial dielectric gradation. Such two-dimensionally graded lens structures can be prepared by various methods suggested heretofore, including so-called step construction methods wherein a plurality of blocks of material, concentric cylinders, or shells exhibiting proper individual dielectric constants are assembled to effect a stepwise approximation of a theoretical refractive index gradation, e.g. a Luneberg or modified Luneberg gradation. In accordance with a preferred technique, however, the several lens wafers **10** are fabricated by a technique of the type described in my prior copending application Ser. No. 217,751, filed Aug. 17, 1962, now U.S. Patent No. 3,256,373 for "Method of Forming a Cylindrical Dielectric Lens." The use of such a technique results in the fabrication of a cylindrical mass of dielectric material having a substantially continuous and accurately controllable variation in dielectric constant in radial directions; and this technique permits the ready formation of various different dielectric gradations for the different ones of lens wafers **10**, as will be described hereinafter. The materials employed in forming lens wafers **10** can comprise either natural or artificial dielectric materials; and when the material constitutes an artificial dielectric, it preferably comprises needle-shaped aluminum slivers distributed with varying concentration (in accordance with the desired dielectric gradation) through a low-loss polystyrene foam supporting matrix, all as described in my prior copending applications identified above.

A lens structure constructed to exhibit a Luneberg gradation may comprise a cylindrical mass of dielectric material having a varying dielectric constant in radial directions between the center and outermost periphery of said mass, varying in accordance with theoretical equations taught by Luneberg (and discussed, for example, in my U.S. Patent No. 3,256,373) so as to define a lens focal point F (see FIGURE 2) located at the outer periphery of said mass. Energy from a source located at the lens focal point F is refracted within the lens medium due to the varying dielectric constants of said medium, so as to emerge in a substantially plane wave, designated **12** in FIGURE 2. If a reflector surface is mounted on the surface of the lens in the region of its focal point F, energy entering the lens, e.g. as a plane wave **12**, is refracted within the lens to the aforementioned focal point F, and is then reflected back through the lens so as once more to emerge from the lens as a plane wave. These concepts are in themselves well-known to those skilled in the art.

The actual location of the focal point F may be displaced from the peripheral surface of the lens by appropriate variation of the particular dielectric gradation employed in the lens itself. The focal point may, for example, be displaced to any desired point internal of the lens, e.g., a point such as that designated F′ in FIGURE 2; or it may be displaced to any desired point external of the lens periphery, e.g. a point such as that designated F″ in FIGURE 2. When the focal point F is located at the lens periphery, as shown in FIGURE 2, the lens is said to exhibit a Luneberg gradation. However, if the focal point is displaced to a point such as F′ or F″, the lens can be said to exhibit a "modified" Luneberg gradation, i.e. the lens is a "modified" Luneberg lens.

The various gradations needed to achieve modified Luneberg lenses having focal points displaced at various different distances from the lens periphery, are discussed in a treatise, "General Solution of the Luneberg Lens Problem," by Samuel P. Morgan, Journal of Applied Physics, volume 29, September 1958. Morgan discusses various dielectric gradients which can be used to achieve modified Luneberg lenses having the lens focal point displaced from the lens surface by a desired amount; and provides tables listing such dielectric values (and dielectric gradations) in terms of a factor *s*, which is the distance of the focus from the center of the lens normalized to the radius of the lens. The meaning of this factor *s* can be appreciated by reference to the diagram appearing at the upper right corner of FIGURE 5. Knowing the radius of the lens R, and knowing the distance F between the center of the lens and the lens focal point, the factor *s* comprises the ratio between F and R. Thus, for example, if *s* equals 1.05, the focal point of the lens occurs at a position external of the lens periphery, displaced from the lens center by an amount 5% greater than the lens radius. Similarly, if *s* equals 1.01, the focal point occurs at a point exterior of the lens by an amount 1% greater than the radius of the lens. When the factor *s* equals 1, the focal point occurs on the lens surface; and the corresponding gradation is in accordance with the theoretical Luneberg gradation.

The various tables of gradients supplied in the aforementioned Morgan article, can be plotted, for different vales of *s*, in accordance with the graphical representation of FIGURE 5. Two such curves have been shown in FIGURE 5, one for the parameter *s* equals 1.00 (which is the Luneberg gradation), and another for *s* equals 1.05, which is a modified Luneberg gradation wherein the focal point is displaced to a position external to the lens by an amount 5% greater than the lens radius. Using the Morgan tables, a complete family of curves may be plotted in a manner similar to that shown in FIGURE 5, for various values of *s* such as 1.01, 1.02, 1.03, and 1.04 (all of which curves would lie between the two curves actually shown in FIGURE 5), and for other values of *s* such as would produce curves lying above or below the two curves actually shown in FIGURE 5. By using such a set of curves and/or by interpolation between the various tabulations given in the Morgan article, one can establish the particular dielectric gradation needed to achieve a modified Luneberg lens having its focal ponnt displaced in any desired manner relative to the theoretical focal point of a true Luneberg lens.

The factor *s* discussed in the aforementioned Morgan article can be considered not only to indicate the actual position of the lens focal point, but also can be treated as indicating the electrical diameter of a modified Luneberg lens relative to that of a lens having a true Luneberg gradient. This relationship is shown in FIGURE 4B for several lenses of different sizes; the electrical diameter change $\Delta\phi$ is plotted as a function of the parameter *s*. If approached from this point of view, therefore, the data provided by Morgan can be treated as setting forth a series of modified Luneberg gradations which can be used to provide modified Luneberg lenses of various different electrical lengths. This concept has been employed in the fabrication of the structures constituting the present invention.

Returning now to FIGURE 1, the various lens wafers **10** are constructed to exhibit various different dielectric gradations, and constitute a plurality of modified Luneberg lenses so arranged that each wafer exhibits an electrical length which is somewhat greater than that of the wafer immediately below. If, for example, the uppermost wafer **10** in FIGURE 1 can be considered as having a true Luneberg gradation, the next lower wafer might have a modified gradation corresponding to *s* equals 1.01; the wafer next below might have a gradation corresponding to *s* equals 1.02, etc. These particular values of *s* are merely illustrative, as will appear hereinafter. By selecting these different dielectric gradations, and by separating the various wafers **10** by intervening conductive surfaces **11** so

that the wafers **10** act independently of one another, the resultant array comprises a plurality of stacked lens sections having successively smaller electrical diameters, and operates to provide successively short delays to incident energy so that a phase change occurs from one section to the next adjacent section. If a plane wave of incoming energy is positioned adjacent the periphery of the lens as at **13** (comprising a line source of incoming energy produced either by an energy source, or by a reflector surface), the portions of that line of energy associated with the various different waves **10** can be treated as comprising point sources for said different wafers **10**. The energy passing through the several wafers **10** (along paths of the type diagramatically illustrated in FIGURES 1 and 2) emerges at **14** (see FIGURE 1) with successively different phase delays from section to section. The emerging wave front **14** is, as illustrated, disposed at an angle to the direction of the incoming wave front **13**. The actual beam angle of the emerging wave front **14** depends upon the magnitude of the delay which is achieved from section to section of the several wafers **10**.

Considering now the geometry illustrated in FIGURE 1, if we assemble a stack of two-dimensional lenses all of which have the same height h, and if we know the desired vertical beam-angle β to be produced by the resultant stack, the change in electrical path length $\Delta\phi$ becomes equal to $h \tan \beta$. This equation can be plotted for various values of β, and for various thicknesses h (in wavelength dimensions) to provide a family of curves of the type shown in FIGURE 4A. The curves of FIGURE 4A are useful in determining the change in electrical path length $\Delta\phi$ which is required from section to section of a stack such as is shown in FIGURE 1, to produce any desired vertical beam-angle β. By way of example, if the various wafers **10** all have a thickness h which is one-half wavelength at the operating frequency, and if we know that an emerging beam angle of 5° is desired, one can employ curves such as that shown in FIGURE 4A to determine (as shown by the dotted lines on FIGURE 4A), that a $\Delta\phi$ of substantially 15° must be provided from one wafer section **10** to the next in the stacked array of FIGURE 1. This figure of $\Delta\phi$, and the other parameters mentioned, are merely approximated for purposes of discussion herein, and with no attempt at precise accuracy.

The total phase delay produced in a given wafer **10** depends not only upon the gradation of that wafer, but also depends upon its diameter D. The actual phase delays produced in lens sections having various different modified Luneberg gradations can be plotted as a function of lens diameter D to produce a family of curves of the type shown in FIGURE 4B. From such a family of curves, it will be seen (again, approximating only) that if a modified Luneberg gradation corresponding for example to s equals 1.01 is selected, a wafer having that gradation and a diameter of six wavelengths will exhibit a phase delay of approximately 10° greater than that which would be produced by a true Luneberg lens of like diameter; would produce an increased phase delay of approximately 15° if the lens diameter were ten wavelengths; would produce an increased phase delay of approximately 30° if the lens diameter were twenty wavelengths, etc. One can, accordingly, employ curves of the types shown in FIGURES 4A and 4B to determine (knowing the lens thickness and diameter) just what value of $\Delta\phi$ should be provided from section to section to achieve a desired vertical beam angle β; and one can then use the information so derived in conjunction with the Morgan tabulations, or in conjunction with graphical representations thereof (as in FIGURE 5), to determine the precise gradients which are needed for the various individual wafers **10**.

By way of example, let us assume that the various wafers **10** each have a thickness h of one-half wavelength, and that said wafers **10** all have a diameter D of twenty wavelengths. Let us further assume that we wish to acheive a desired vertical beam angle β of 5°. Using the parameter h in conjunction with FIGURE 4A, it will be seen that the $\Delta\phi$ needed from section to section to achieve the beam angle β of 5° will be approximately 15° (again, approximating for purposes of illustration only). If this 15° value of $\Delta\phi$ is now used in conjunction with the 20λ curve D of FIGURE 4B, the assumed data will define a gradation (point A of FIGURE 4B) corresponding to s equals 1.005 (again, approximating). If, therefore, we start with a first wafer **10** having a true Luneberg gradation, and then add to that first wafer another wafer which has a gradation corresponding to s equals 1.005, a difference in electrical path length $\Delta\phi$ of 15° will be produced between these two wafers. A third wafer, having a gradient which would produce a still additional 15° delay, will have a gradient corresponding to point B in FIGURE 4B, i.e. s equals 1.01. The fourth wafer would correspond approximately to point C in FIGURE 4*b*, i.e. s equals 1.015. A similar analysis can be used to determine the factors s needed for each successive wafer.

These various factors s, determined by the joint use of FIGURES 4A and 4B, can be converted into specific dielectric gradients by using curves of the types shown in FIGURE 5 (or by use of the Morgan tabulations); and by appropriate interpolation between the different curves of FIGURE 5 or the different tabular values provided by Morgan, the precise gradients needed for any value s can be determined. A stack of lens wafers having these successive different gradients can then be fabricated, with intervening conductive surfaces, in the manner depicted in FIGURE 1, so as to achieve the desired vertical beam angle for an incoming line of energy.

The techniques described are also useful in producing an omniazimuthal lens reflector which provides an energy return along a wave front which is angularly displaced to the direction of incoming enery. An arrangement of this type is shown in FIGURE 3. The lens portion of the structure comprises a plurality of stacked wafers **20**, constructed in accordance with the various considerations already discussed. Reflector strips such as **21**, **22**, and **23** (which is hidden), can then be disposed about the outer periphery of the stacked wafers **20**, with each of said reflectors **21**, **22**, **23**, extending about the outer periphery of the lens stack through an angle of approximately 120°, and in substantially non-overlapping relation to other ones of said reflector surfaces. In the alternative, the reflector strips **21**, **22**, and **23**, may take the form of a continuous helix of reflective material disposed about the periphery of the stack **20**. In operation, energy coming from any direction will pass through a group of the lens wafers in stack **20** to a reflector surface, whereafter the energy will be returned due to reflection from said surface and will emerge from the lens stack.

Since, in this reflector embodiment of the invention, energy passes through the individual lens wafers twice before it emerges, any individual ray of energy experiences twice the phase delay which would be effected during a single traverse. Accordingly, the vertical beam angle of the emerging energy will be twice that which would occur if the incident energy merely passed through the lens once. The delay characteristics for the individual sections or wafers comprising stack **20** therefore need be only one-half that which would be the case for the lens construction already described in reference to FIGURE 1; and this consideration should be taken into account when using curves of the types already described in reference to FIGURES 4A and 4B. By way of example, if it is desired to achieve a vertical beam angle of 10° using the reflector structure of FIGURE 3, parameters should be selected which would correspond to a vertical beam angle of only 5° in a lens configuration of the type shown in FIGURE 1; and the double travel of energy through the individual wafers of the reflector structure shown in FIGURE 3 will thereupon achieve the desired 10° vertical beam angle by the time that the energy emerges for return purposes.

While I have thus described preferred embodiments of the present invention, many variations will be suggested to those skilled in the art; and it must therefore be understood that the foregoing description is intended to be illustrative only and not limitative of my invention. All such variations and modifications as are in accord with the principles described are meant to fall within the scope of the appended claims.

Having thus described my invention, I claim:

1. An angular propagation lens structure comprising a plurality of substantially cylindrical dielectric lenses stacked one upon the other, means providing conductive interfaces between adjacent lenses in said stack. the diameter of the lenses at the opposing ends of said stack being substantially the same as the diameter of a lens within said stack, each of said lenses in said stack exhibiting a dielectric gradation in radial directions, the radial dielectric gradations for different ones of said stacked lenses differing from one another whereby the effective electrical lengths of said lenses, to incident energy passing through said lenses between said conductive interfaces, differs from one to another of said stacked lenses.

2. The lens structure of claim 1 wherein the radial dielectric gradations for at least some of said stacked lenses comprise modified Luneberg gradations.

3. The lens structure of claim 1 wherein the radial dielectric gradation for at least one of said lenses comprises a Luneberg gradation.

4. The lens structure of claim 1 wherein said differing dielectric gradations are arranged to produce a substantially fixed difference in electrical length between adjacent ones of said stacked lenses, the electrical lengths of said stacked lenses increasing progressively from one to the next of said stacked lenses.

5. The lens structure of claim 1 including curved reflector strip means extending along the outer periphery of said stacked cylindrical lenses.

6. The lens structure of claim 5 wherein said reflector strip means comprises a plurality of arcuate strips positioned at different axial levels about said stacked lenses in staggered substantially non-overlapping relation to one another.

7. The lens structure of claim 1 wherein each of said cylindrical lenses comprises metallic particles supported in a dielectric matrix, the concentration of metallic particles in the matrix of any given one of said lenses varying smoothly in radial directions between the center and outer periphery of that lens to achieve the dielectric gradation for said lens.

8. The lens structure of claim 7 wherein the diameters of all said stacked lenses are equal, the thicknesses of all said lenses in directions normal to the lens interfaces also being equal.

9. The lens structure of claim 1 wherein said means providing conductive interfaces comprises layers of metallic material disposed between said stacked lenses for assuring that each of said lenses operates to refract energy passing therethrough substantially independently of the others of said stacked lenses.

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ELI LIEBERMAN, *Primary Examiner.*