March 18, 1958 L. BATCHELDER 2,827,620

BEAM-FORMING SYSTEMS

Filed Jan. 30, 1953 3 Sheets-Sheet 1

FIG. 1

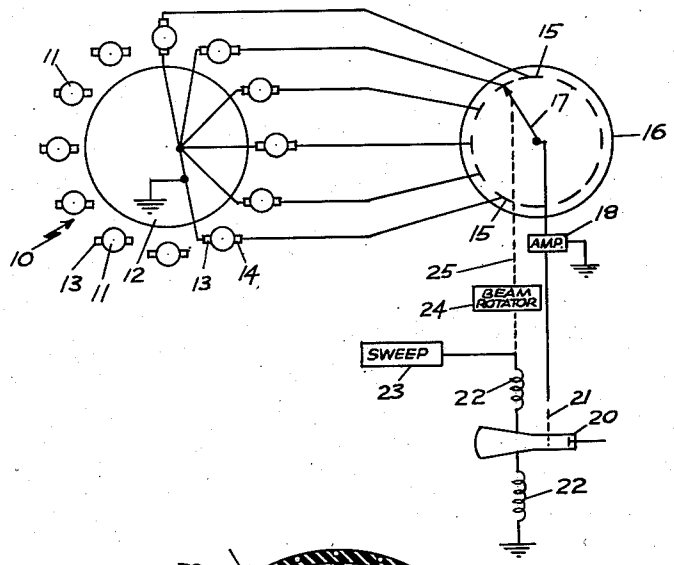


FIG. 6

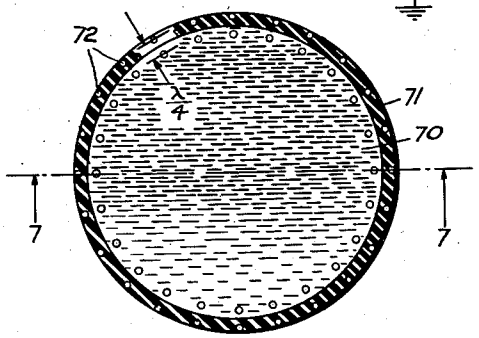
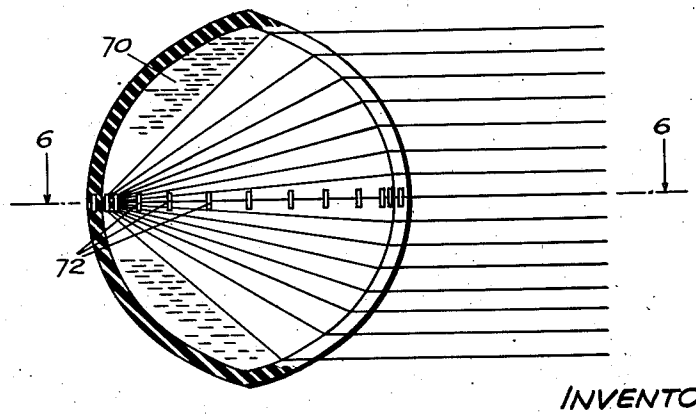


FIG. 7



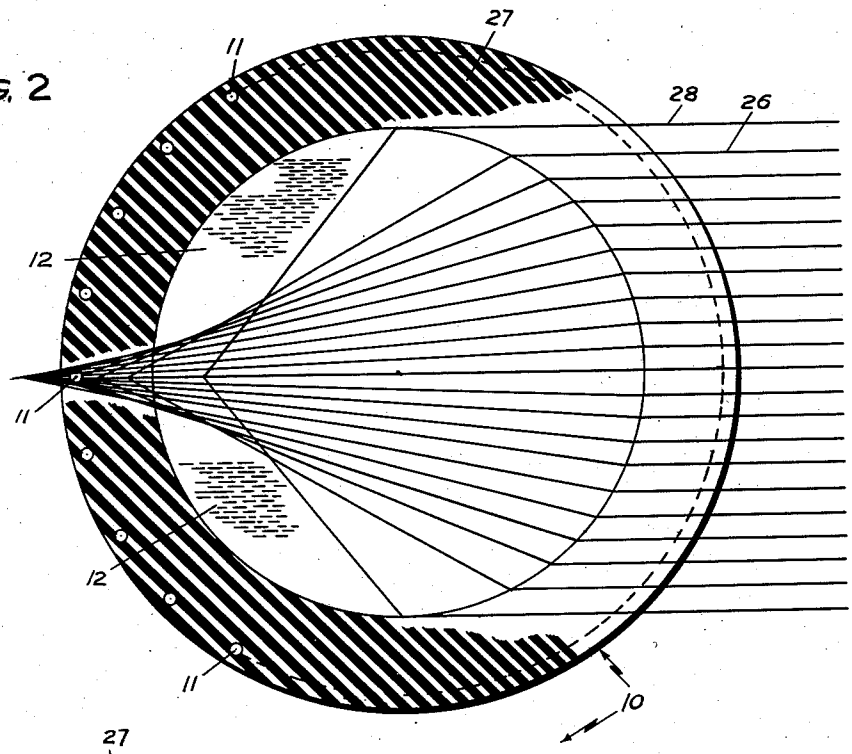
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BEAM-FORMING SYSTEMS

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FIG. 2



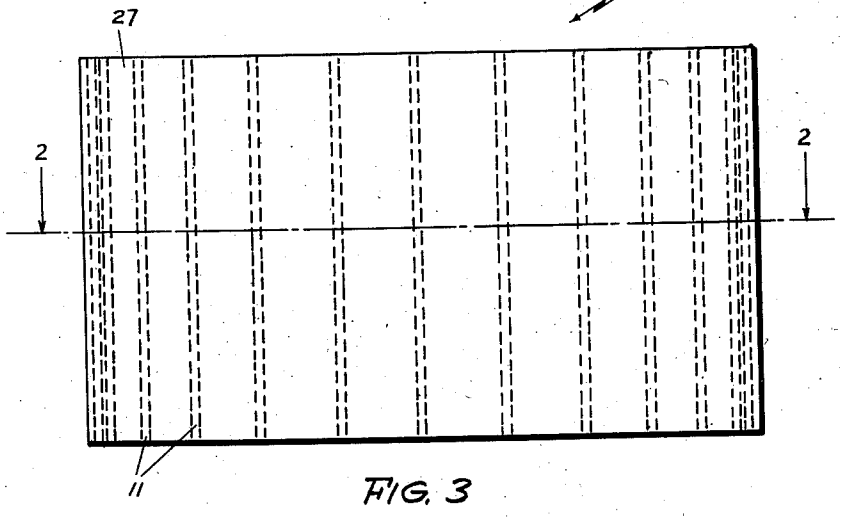


FIG. 3

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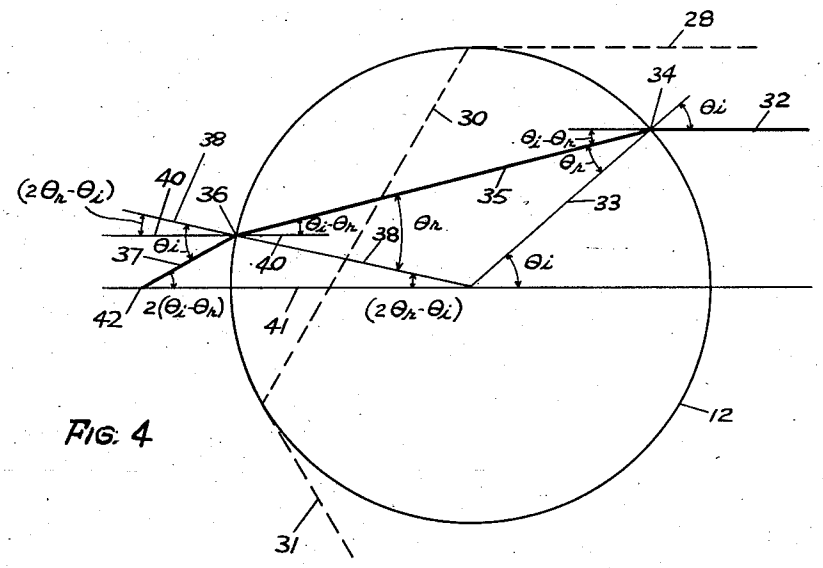


FIG. 4

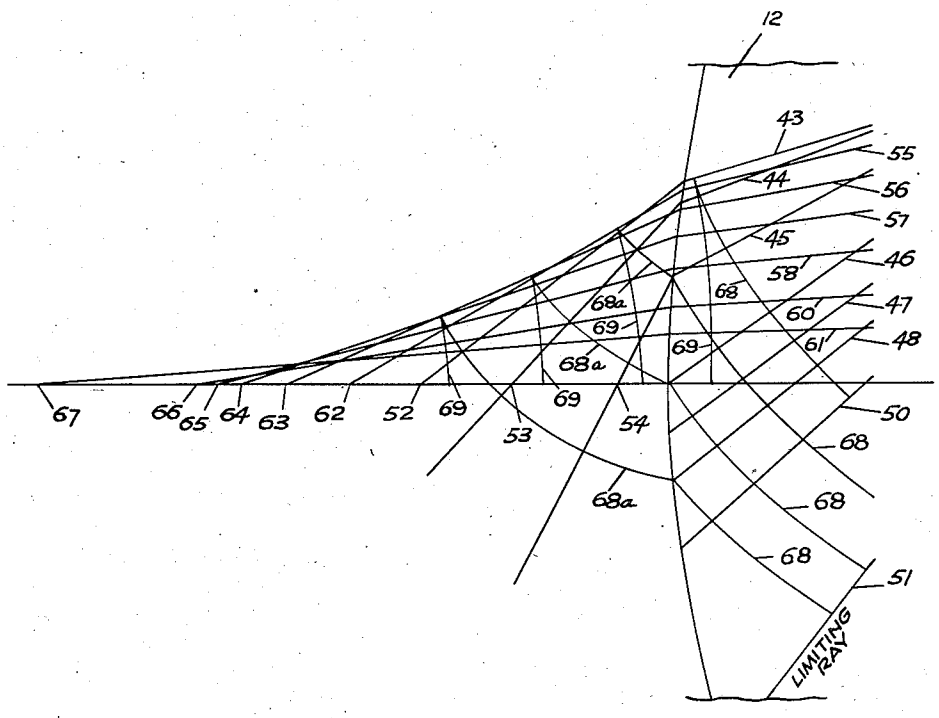


FIG. 5

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United States Patent Office 2,827,620
Patented Mar. 18, 1958

2,827,620

BEAM-FORMING SYSTEMS

Laurence Batchelder, Cambridge, Mass., assignor to Raytheon Manufacturing Company, Newton, Mass., a corporation of Delaware

Application January 30, 1953, Serial No. 334,323

17 Claims. (Cl. 340—6)

This invention relates to improvements in the beam-forming system for an echo-ranging apparatus utilizing underwater sound.

In the copending application of Stanley R. Rich, Serial No. 14,017, filed March 10, 1948, now Patent No. 2,786,193, dated March 19, 1957, there is disclosed an echo-ranging system wherein a plurality of substantially omnidirectional transducers are permanently fixed in position relative to each other. By phasing the operation of said transducers, the overall transducer system may be made to operate as a directional system, that is, one having directional receiving or propagating characteristics.

The aforementioned application discloses a particular electrical system adapted to accomplish the phasing of the transducers so that they will operate with any of a plurality of desired directions. Briefly, this is accomplished by feeding an electrical delay line system from each transducer. Energy is coupled from each of the delay lines to various points along their length corresponding to various delay periods. A plurality of circuits is fed by the energy coupled by each of said delay lines, each circuit being fed energy from each of the delay lines. The delays of the energy feeding the circuits are phased in such a manner that each circuit will produce a signal at its output in response to the impingement of a signal on the transducer elements from a particular direction. Each circuit is responsive to signals from a different direction. As a result, by selecting the output from a particular circuit, any desired direction of the transducer system may be had. In order to successively connect the outputs of each of the circuits to an indicating device, a switching tube is used, said switching tube comprising, for example, a plurality of electrodes, each electrode being successively struck by a beam. The output of said switching tube is, therefore, successively the output of each of the circuits. This output is fed to the indicating means as, for example, the grid of a cathode ray tube, the beam of which is rotated in synchronism with the beam of the switching tube. Thus, the appearance of a signal at the transducer system from any direction will produce a signal at the output of one of the circuits, which circuit will depend upon the direction of the received signal, and the reception of such a signal will produce a bright spot on the cathode ray tube screen at an angular position indicative of the direction of arrival of the received signal.

The present invention discloses the use in a sonar system, such as that described above, of an array of transducers grouped in a circular array about a lens for compressional wave energy with each transducer positioned at the point where the major part of a beam of energy impinging on the lens from one of several predetermined directions is concentrated by the lens. By the use of this lens arrangement, the elaborate and carefully adjusted phasing network of the cited Rich application is not needed as the lens and commutator accomplish scanning by connecting the indicator input successively

to transducers at which the energy approaching from selected directions is concentrated by the direction of the lens. In the case of a cylindrical lens with a circular cross section, this energy is concentrated in a linear region of a width equal to about a tenth of the diameter of the lens and extending for approximately this distance beyond the perimeter of the lens. A lens having an elliptical cross section would produce a sharper focus, but such a lens would only be useful in concentrating the energy of a beam of compressional waves from a single direction, whereas the cylindrical lens gives a focus, even though not sharp, for energy from any direction.

A compromise shape between an elliptical cross section and a cylindrical lens is one that is lemon shaped, that is, its shape is obtained by rotating an elliptical arc about an axis perpendicular to the plane of radiation to be scanned. It is convenient to have the thickness of the lens equal to the focal length of the elliptical arc. In this case, the transducers are placed about the perimeter of the lens in the plane that is to be scanned with each transducer at the focal point for compressional wave energy coming from a particular direction.

In a sonar system of this type, an omnidirectional transmitting transducer would preferably be placed above or below the lens and coaxial with it. While the lens and peripheral transducers could be used to transmit compressional wave energy, as well as to receive such energy, the physical size of the transducers necessary to propagate a useful amount of energy over any useful range might well be so great as to make the use of this arrangement for transmitting compressional wave energy impracticable. For receiving purposes, the transducers need only be in the form of pencils of piezo-electrical material having a diameter in the order of one-eighth of an inch. If the lens of this arrangement is made of a material having a high index of refraction, with respect to that of the medium in which the system is to be used, the array can be made in a very compact space that will depend in part upon the operating wave length. A compact structure such as this is of particular advantage when using longer wave lengths with their desirable propagation characteristics.

Other and further advantages of this invention will be apparent as the description thereof progresses, reference being had to the accompanying drawings, wherein:

Fig. 1 is a schematic diagram of the system in which the invention is used;

Fig. 2 is a section of a cylindrical lens of the invention taken along the line **2—2** in Fig. 3 in the plane to be scanned and diagrammatically showing how a beam of compressional wave energy is concentrated by the lens;

Fig. 3 is a side view of the lens of Fig. 2;

Fig. 4 is a diagram illustrating the double refraction effect of a full cylindrical lens;

Fig. 5 is a diagram of the effect of the phenomenon of Fig. 4 with respect to a beam of rays shown on a large scale;

Fig. 6 is a section of another embodiment of the lens of the invention taken along line **6—6** of Fig. 7 in the plane to be scanned and showing diagrammatically how it focuses a beam of compressional wave energy; and

Fig. 7 is a section of the lens taken along the line **7—7** of Fig. 6.

In Fig. 1, the reference numeral **10** designates the lens and transducer arrangement of the invention generally. This array is shown as comprising twelve individual transducers **11**, for the purpose of illustration, although for practical purposes a larger number may be desirable. In Fig. 1, the transducers **11** are shown grouped about a lens **12**. Each of these transducers has a pair of terminals **13** and **14**. The terminal **13** of each pair is con-

nected to ground. The terminal 14 of each pair is connected to an electrode 15 of a commutator device 16.

Only six of the transducers 11 are shown connected to electrodes 15 of the commutator tube 16. The other six are connected similarly, but these connections are not shown, in order not to unnecessarily complicate the diagram. The transducers 11 may be of any of the well-known types operating on either the piezoelectric or magnetostrictive principles. The commutator tube 16 may be of any of the well-known types, such as the structure disclosed in the copending application of Stanley R. Rich and Edwin E. Turner, Serial No. 655,447, filed March 19, 1946, now U. S. Patent No. 2,684,449.

In Fig. 1, the beam of such a tube is represented as a switch arm 17 coupled to an amplifier 18. However, this arm 17 is to be understood as being purely symbolic as it may, in fact, be a beam of electrons. The output of the amplifier 18 is coupled to the input of an indicating means 20 which is shown in Fig. 1 as a cathode ray tube having a grid 21 to which the output of the amplifier 18 is coupled and as also having means to sweep the beam in a spiral trace.

The spiral sweep generator means for the indicator tube 20 is shown in Fig. 1 as a set of coils 22 designed to radially deflect the beam of the tube 20 at a rate linear with time in response to impulses from a sweep generator 23. These deflection coils 22 are rotated about the neck of the tube 20 by a synchronized beam rotator 24 that is also adapted to synchronously rotate the beam about the commutator tube 16 through the connection represented by the dotted line 25. This again is symbolic of the relationship which may be effected by either mechanical or electrical means.

As pointed out above, the individual transducers 11 may be of either the piezo-electric or magnetostrictive types. The most convenient form of transducer for this type of array is probably a barium titanate tube in the form of a small pencil, one-eighth of an inch in diameter, having a conductive layer on the inside and the outside surfaces to carry off any electrical potentials developed across the crystal by compressional wave energy impinging upon it.

Fig. 2 shows schematically how a beam of compressional wave energy impinging upon a liquid lens 12 will be concentrated in a limited region. In order to do this, the section lines have been omitted in the region where the rays are shown, in the interest of clarity. Rays 26, coming from a given direction, impinge upon a liquid cylindrical lens 12 after passing through a skin 27 of a material such as synthetic rubber having substantially the same transmission properties for compressional wave energy as the medium in which the equipment is to be used, usually sea water. The skin can be of any material so long as it is thin enough so as not to appreciably affect the operation of the lens. The liquid of the lens provides a velocity of sound that is as low as possible compared to that provided by the medium in which the system is to be used consistent with a reasonable acoustic impedance match. It has been found that carbon tetrachloride gives an index of refraction with respect to sea water of 1.6. The impedance match of carbon tetrachloride with sea water is very good. The lens 12 may also be formed of a suitable solid material. If the ray 28 is considered to be on the outermost edge of a beam, impinging upon the lens from a given direction, it will be deflected towards the center of the lens. Rays further toward the axis of the impinging beam are not deflected as much. Such rays tend to concentrate at points further and further beyond the center of the lens. It can be shown that the major part of the energy in a beam of compressional waves will be concentrated in a region beyond the lens but within a distance equal to a tenth of the thickness of the lens. The transducers 11 are arranged in a circle about the axis of the lens. This circle has a radius about a tenth greater than that of the lens. These transducers can most conveniently be supported by imbedding them in the skin of the lens if it is made thick enough for this purpose, as shown in Fig. 2.

Fig. 2 is somewhat incomplete, in that it fails to take into account the second refraction of a ray as it leaves the lens.

Fig. 4 shows in more detail than Fig. 2 how the rays will be refracted and focused by the lens 12. If the dotted line 28 is considered as representing one of the two outermost rays of the impinging beam, it will be seen to be deflected towards the center of the lens 12 along the path 30, and when it reaches the skin of the lens 12 it will be again deflected along the line 31. The line 32 represents a ray impinging upon the lens at an arbitrary position. This ray makes an angle θ_i with a radius 33 drawn through the point of impingement 34. This ray will be refracted to follow a path 35 which makes an angle θ_r with the radius 33. As determined by the formula

$$\frac{\sin \theta_i}{\sin \theta_r} = n$$

where n=the index of refraction.

When this refracted ray 35 again reaches the skin at the point 36, it will be refracted along a path 37 making the same angle θ_i with a radius 38 drawn through the point 36. A line 40 drawn through the point 36 parallel to the incident ray 32 will make an angle $\theta_i - \theta_r$ with the path 35 of the ray through the lens. This line 40 makes an angle $2\theta_r - \theta_i$ with the continuation of the radius 38. The difference between this angle and the angle of incidence is twice the difference between the angle of incidence and the angle of refraction. If a line 41 is drawn through the center of the lens in the direction of the beam, it will intersect the ray 37 at a point 42 to form a triangle between the center of the lens and the points 36 and 42. The angle between the ray 37 and the continuation of the radius from the center to the point 42 is equal to twice the difference between the angle of incidence and the angle of refraction. The angle between the radius 38 and the radius 41 is equal to $2\theta_r - \theta_i$. From this the distance of the point 42 from the skin of the lens can be determined by known principles of geometry. By similar construction, a diagram, such as that of Fig. 5, can be drawn showing where the greater part of the compressional wave energy would be concentrated along the axis of the beam beyond the lens. In Fig. 5, the lines 43, 44, 45, 46, 47, 48, and 50 represent rays from the outer part of the beam, and line 51 represents the limiting or outermost ray of the beam. It will be seen that ray 43, when passing out of the lens 12, is refracted to intersect the axis of the beam at a point 52 beyond the lens, and rays 44 and 45 are similarly refracted to intersect the axis at points 53 and 54, respectively, while ray 46 intersects the axis at the skin of the lens 12. Rays 47, 48, 50, and 51 intersect the axis at points within the lens. Lines 55, 56, 57, 58, 60, and 61 represent rays from the inner part of the beam. It will be seen that they all are refracted to intersect the axis at points 62, 63, 64, 65, 66, and 67, respectively, beyond the surface of the lens. From an examination of this diagram, it will be seen that a transducer placed in the vicinity of point 63 on the axis will receive a major part of the energy concentrated by the lens 12. The lines 68 represent wave fronts within the lens of such rays as 44 to 50. The lines 68*a* represent these wave fronts beyond the lens. Lines 69 represent the wave front of such rays as 55 through 61.

It is known that a lens of elliptical shape, with an eccentricity equal to the reciprocal of the index of refraction of the material of which the lens is made, will focus a beam from one particular direction at a particular point. This principle can be utilized for the purpose of this invention by the use of the lens structure illustrated in Figs. 6 and 7. Section lines have been omitted in these

figures in order to show the rays clearly. A lens of this type is of a shape that may be considered as being formed by the revolution of an elliptical arc of the desired shape about an axis. The maximum thickness of this lens measured perpendicular to the axis should be equal to the focal distance of the generating elliptical arc, so that energy impinging on the lens from any direction perpendicular to the axis will be focused at a point on the opposite surface of the lens where a transducer may be mounted. Any desired number of transducers may be mounted at the surface of such a lens in a plane perpendicular to the axis and passing through the thickest part of the lens in Fig. 7. The lens proper is represented by the numeral 70 and is surrounded by a skin 71. The materials of the lens and the skin are selected with the same considerations in mind as the materials for the lens and skin of the lens shown in Figs. 2 and 3. The transducers 72 are mounted, as described above, around the surface of the lens, as can be seen in Fig. 6. Better results can be obtained if two transducers are mounted in each position spaced apart a distance equal to one-quarter of a wavelength at the operating frequency. The axes of each transducer lie along the radius of the lens in this plane. Such an arrangement of the transducers, when associated with a suitable time delay network, gives a cardioid reception pattern to the transducers and prevents the reception of interfering signals from the back of the lens.

This invention is not limited to the particular details of construction, materials and processes described, as many equivalents will suggest themselves to those skilled in the art. It is, accordingly, desired that the appended claims be given a broad interpretation commensurate with the scope of the invention within the art.

What is claimed is:

1. In a scanning system of the echo-ranging type utilizing compressional wave energy, a transducer array comprising a plurality of transducers supported in spaced apart relationship in a common plane in a circular pattern, a lens for compressional wave energy of cylindrical shape positioned with its major axis of symmetry perpendicular to the plane of the pattern of the array of transducers and passing through its center, said lens formed in a manner to cause parallel rays of said energy impinging on one side to be concentrated in the region of the transducers on the opposite side.

2. In a scanning system of the echo-ranging type utilizing compressional wave energy, a transducer array comprising a plurality of transducers supported in spaced apart relationship in a common plane in a circular pattern, a lens for compressional wave energy formed of a material having a higher index of refraction for compressional wave energy than the medium in which the system is used, positioned with its major axis of symmetry perpendicular to the plane of the pattern of the array of transducers and passing through its center and with its radius in this plane less than the radius of the circular pattern of the transducers, said lens formed in a manner to cause parallel rays of said energy impinging on one side to be concentrated in the region of the transducers on the opposite side.

3. In a scanning system of the echo-ranging type utilizing compressional wave energy, a transducer array comprising a plurality of transducers supported in spaced apart relationship in a common plane in a circular pattern, a fluid lens for compressional wave energy formed of a material having a higher index of refraction for compressional wave energy than the medium in which the system is used, contained within a skin of a material having the same transmission characteristics for compressional wave energy as the medium in which the system is used, positioned with its major axis of symmetry perpendicular to the plane of the pattern of the array of transducers and passing through its center and with its radius less than the radius of the circular pattern of the transducers, said lens formed in a manner to cause parallel rays of said energy impinging on one side to be concentrated in the region of the transducers on the opposite side.

4. In a scanning system of the echo-ranging type utilizing compressional wave energy, a transducer array comprising a plurality of transducers supported in spaced apart relationship in a common plane in a circular pattern, a lens for compressional wave energy of cylindrical shape formed of a material having a higher index of refraction for compressional wave energy than the medium in which the system is used, positioned with its major axis of symmetry perpendicular to the plane of the pattern of the array of transducers and passing through its center and with its radius less than the radius of the circular pattern of the transducers, said lens formed in a manner to cause parallel rays of said energy impinging on one side to be concentrated in the region of the transducers on the opposite side.

5. In a scanning system of the echo-ranging type utilizing compressional wave energy, a transducer array comprising a plurality of transducers supported in spaced apart relationship in a common plane in a circular pattern, a fluid lens for compressional wave energy of cylindrical shape formed of a material having a higher index of refraction for compressional wave energy than the medium in which the system is used, contained within a skin of a material having the same transmission characteristics for compressional wave energy as the medium in which the system is used, positioned with its major axis of symmetry perpendicular to the plane of the pattern of the array of transducers and passing through its center and with its radius less than the radius of the circular pattern, said lens formed in a manner to cause parallel rays of said energy impinging on one side to be concentrated in the region of the transducers on the opposite side.

6. In a scanning system of the echo-ranging type utilizing compressional wave energy, a transducer array comprising a plurality of transducers supported in spaced apart relationship in a common plane in a circular pattern, a lens for compressional wave energy of a shape formed by rotating a portion of an ellipse about an axis perpendicular to the plane of the pattern of the array of transducers and passing through its center and with the transducers positioned at the locus of focus of the ellipsoid surface so that parallel rays of said energy impinging on one side will be concentrated in the region of the transducers on the opposite side.

7. In a scanning system of the echo-ranging type utilizing compressional wave energy, a transducer array comprising a plurality of transducers supported in spaced apart relationship in a common plane in a circular pattern, a lens for compressional wave energy formed of a material having a higher index of refraction for compressional wave energy than the medium in which the system is used, of a shape formed by rotating a portion of an ellipse about an axis perpendicular to the plane of the pattern of the array of transducers and passing through its center and with the transducers positioned at the locus of focus of the ellipsoid surface on that surface so that parallel rays of said energy impinging on one side will be concentrated in the region of the transducers on the opposite side.

8. In a scanning system of the echo-ranging type utilizing compressional wave energy, a transducer array comprising a plurality of transducers supported in spaced apart relationship in a common plane in a circular pattern, a fluid lens for compressional wave energy formed of a material having a higher index of refraction for compressional wave energy than the medium in which the system is used, contained within a skin of a material having the same transmission characteristics for compressional wave energy as the medium in which the system is used, of a shape formed by rotating a portion of an

ellipse about an axis perpendicular to the plane of the pattern of the array of transducers and passing through its center and with the transducers positioned at the locus of focus of the ellipsoid surface on that surface so that parallel rays of said energy impinging on one side will be concentrated in the region of the transducers on the opposite side.

9. In a scanning system of the echo-ranging type utilizing compressional wave energy, a transducer array comprising a plurality of transducers supported in spaced apart relationship in a common plane in two concentric circular patterns spaced radially a distance equal to a quarter of the wavelength of compressional wave energy of the operating frequency in the medium in which the system is used, a lens for compressional wave energy positioned with its major axis of symmetry perpendicular to the plane of the pattern of the array of transducers and passing through the center of this pattern, said lens formed in a manner to cause parallel rays of said energy impinging on one side to be concentrated in the region of the transducers on the opposite side.

10. In a scanning system of the echo-ranging type utilizing compressional wave energy, a transducer array comprising a plurality of transducers supported in spaced apart relationship in a common plane in two concentric circular patterns spaced radially a distance equal to a quarter of the wavelength of compressional wave energy of the operating frequency in the medium in which the system is used, a lens for compressional wave energy of a shape formed by rotating a portion of an ellipse about an axis perpendicular to the plane of the pattern of the array of transducers and passing through the center of this pattern and with transducers positioned about the locus of focus of the ellipsoid surface so that parallel rays of said energy impinging on one side will be concentrated in the region of the transducers on the opposite side.

11. A system comprising a group of transducer elements supported in spaced apart relationship in a common plane in a circular pattern, an indicating device, means for successively connecting each of said transducer elements to said indicating device, a lens for compressional wave energy positioned with its major axis of symmetry perpendicular to the plane of the pattern of the array of transducers and passing through the center of the array, said lens formed in a manner to cause parallel rays of said energy impinging on one side to be concentrated in the region of the transducers on the opposite side.

12. A system comprising a group of transducer elements supported in spaced apart relationship in a common plane in a circular pattern, an indicating device, means for successively connecting each of said transducer elements to said indicating device, a lens for compressional wave energy of cylindrical shape positioned with its major axis of symmetry perpendicular to the plane of the pattern of the array of transducers and passing through the center of the array, said lens formed in a manner to cause parallel rays of said energy impinging on one side to be concentrated in the region of the transducers on the opposite side.

13. A system comprising a group of transducer elements supported in spaced apart relationship in a common plane in a circular pattern, an indicating device, means for successively connecting each of said transducer elements to said indicating device, a lens for compressional wave energy formed of a material having a higher index of refraction for compressional wave energy than the medium in which the system is used, positioned with its major axis of symmetry perpendicular to the plane of the pattern of the array of transducers and passing through the center of the array, said lens formed in a manner to cause parallel rays of said energy impinging on one side to be concentrated in the region of the transducers on the opposite side.

14. A system comprising a group of transducer elements supported in spaced apart relationship in a common plane in a circular pattern, an indicating device, means for successively connecting each of said transducer elements to said indicating device, a fluid lens for compressional wave energy formed of a material having a higher index of refraction for compressional wave energy than the medium in which the system is used, contained within a skin of a material having the same transmission characteristics for compressional wave energy as the medium in which the system is used, positioned with its major axis of symmetry perpendicular to the plane of the pattern of the array of transducers and passing through the center of the array, said lens formed in a manner to cause parallel rays of said energy impinging on one side to be concentrated in the region of the transducers on the opposite side.

15. A system comprising a group of transducer elements supported in spaced apart relationship in a common plane in a circular pattern, an indicating device, means for successively connecting each of said transducer elements to said indicating device, a lens for compressional wave energy of a shape formed by rotating an elliptical arc about an axis perpendicular to the plane of the array and passing through the center of the array and with the transducers positioned at the locus of focus of the ellipsoid surface so that parallel rays of said energy impinging on one side will be concentrated in the region of the transducers on the opposite side.

16. A system comprising a group of transducer elements supported in spaced apart relationship in a common plane in a circular pattern, an indicating device, means for successively connecting each of said transducer elements to said indicating device, a fluid lens for compressional wave energy of cylindrical shape formed of a material having a higher index of refraction for compressional wave energy than the medium in which the system is used, contained within a skin of a material having the same transmission characteristics for compressional wave energy as the medium in which the system is used, positioned with its major axis of symmetry perpendicular to the plane of the pattern of the array of transducers and passing through the center of the array and with its radius somewhat less than the radius of the circular pattern of the transducers, said lens formed in a manner to cause parallel rays of said energy impinging on one side to be concentrated in the region of the transducers on the opposite side.

17. A system comprising a group of transducer elements supported in spaced apart relationship in a common plane in a circular pattern, an indicating device, means for successively connecting each of said transducer elements to said indicating device, a fluid lens for compressional wave energy of a shape formed by rotating an elliptical arc about an axis perpendicular to the plane of the array and passing through the center of the array, said lens being formed of a material having a higher index of refraction for compressional wave energy than the medium in which the system is used, contained within a skin of a material having the same transmission characteristics for compressional wave energy as the medium in which the system is used and with the transducers positioned at the locus of focus of the ellipsoid surface so that parallel rays of said energy impinging on one side will be concentrated in the region of the transducers on the opposite side.

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