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Tannaka

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[54] ACOUSTIC LENS

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[73] Assignee: **Hitachi, Ltd.**, Japan

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[52] **U.S. Cl.** .... **181/176;** 340/8 L
[51] **Int. Cl.** **G10k 11/00**
[58] **Field of Search** .... 181/.5 R, 176; 340/8 L; 350/211

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Primary Examiner—Malcolm F. Hubler
Assistant Examiner—H. A. Birmiel
Attorney, Agent, or Firm—Craig & Antonelli

[57] **ABSTRACT**

In order to improve the F-value, a solid acoustic lens is constructed by arranging a plurality of lens blocks adjacent one another in the form of a plane. In the lens block at the center, an incidence surface is a plane surface vertical to the lens axis, while an emergence surface is a concave surface. In each block lens at the outer periphery thereof, an incidence surface is so provided that an incident sound wave may become parallel to the direction connecting the end of an emergence surface on the lens axis side and the lens focus, while the emergence surface is formed of a curved surface by which the incident sound wave is converged to the lens focus.

16 Claims, 8 Drawing Figures

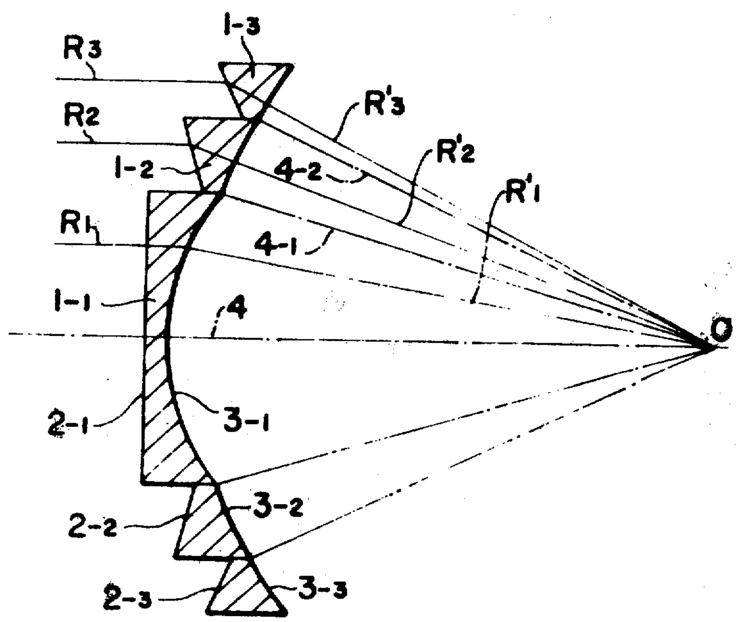


FIG. 1

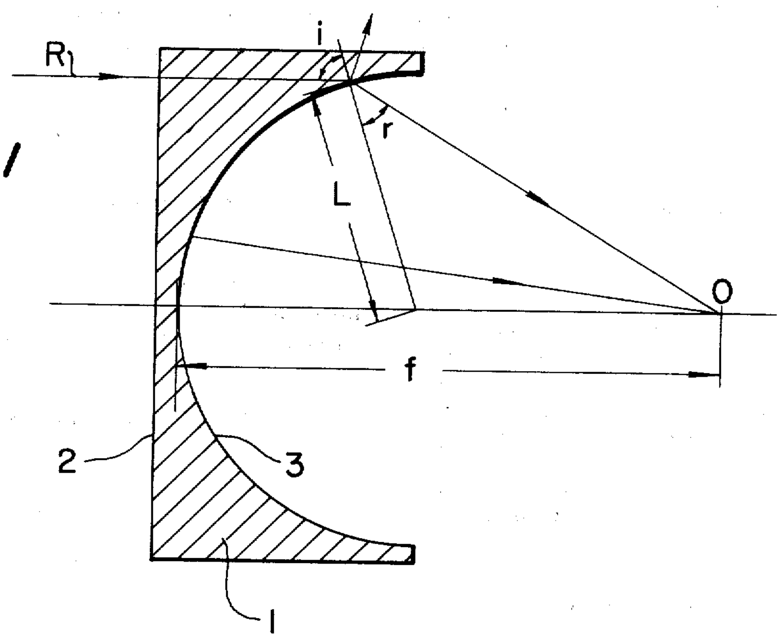


FIG. 2

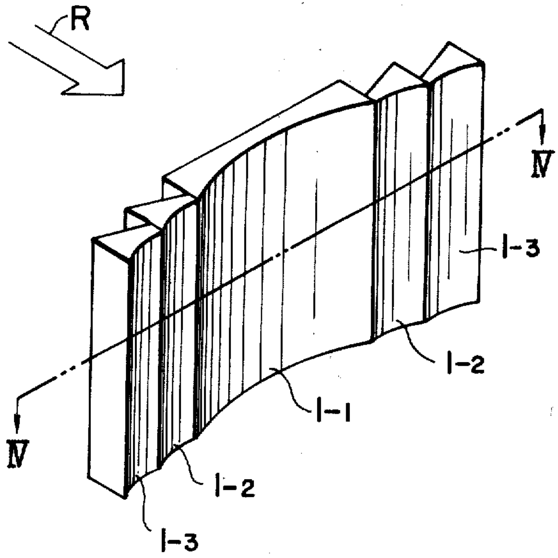


FIG. 3

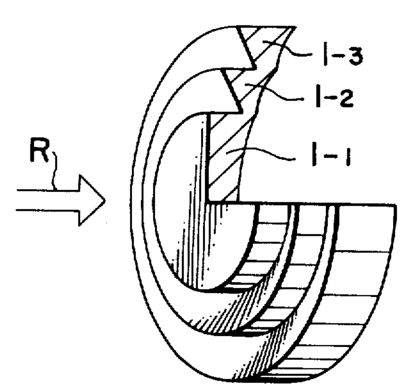


FIG. 4

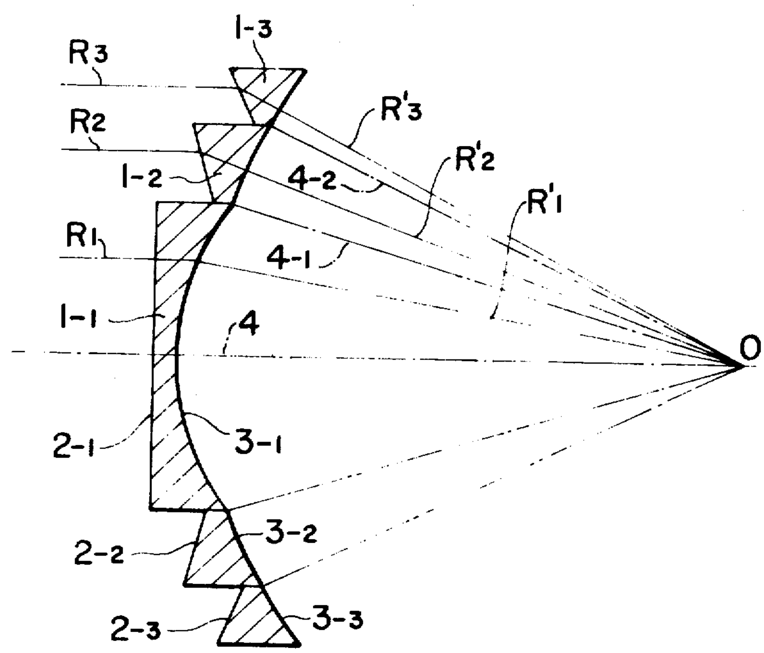

1-3
R3
R'3
R2
R'2
1-2
4-2
R'1
R1
4-1
1-1
4
O
2-1
3-1
3-2
2-2
2-3
3-3

FIG. 5

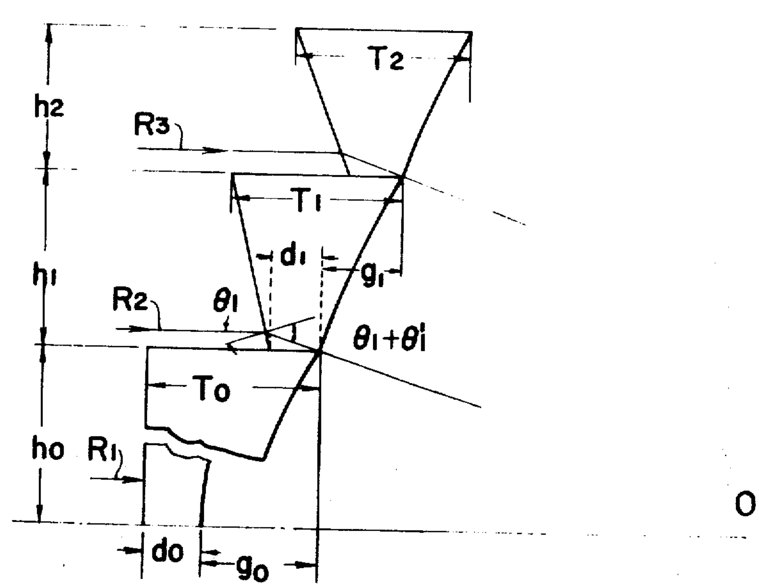

T2
h2
R3
T1
h1
d1
g1
R2
θ1
θ1+θ'1
To
ho
R1
O
do
go

FIG. 6

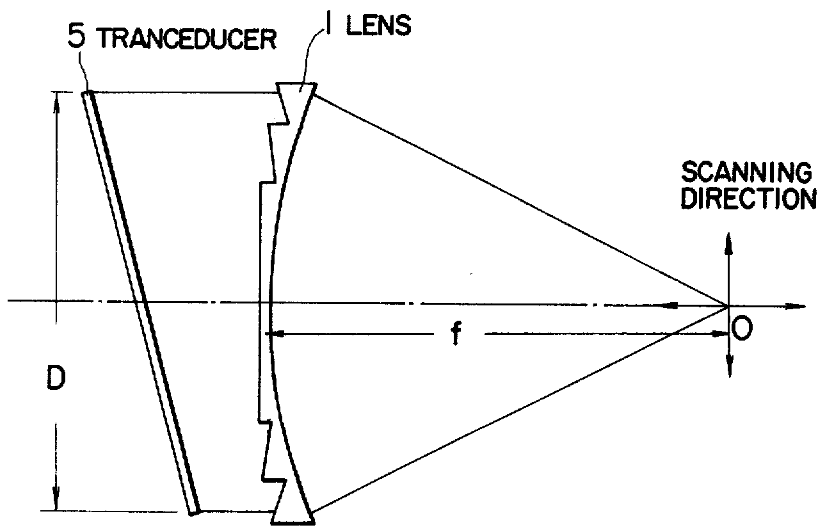

5 TRANCEDUCER
1 LENS
SCANNING
DIRECTION
D
f
O

FIG. 7

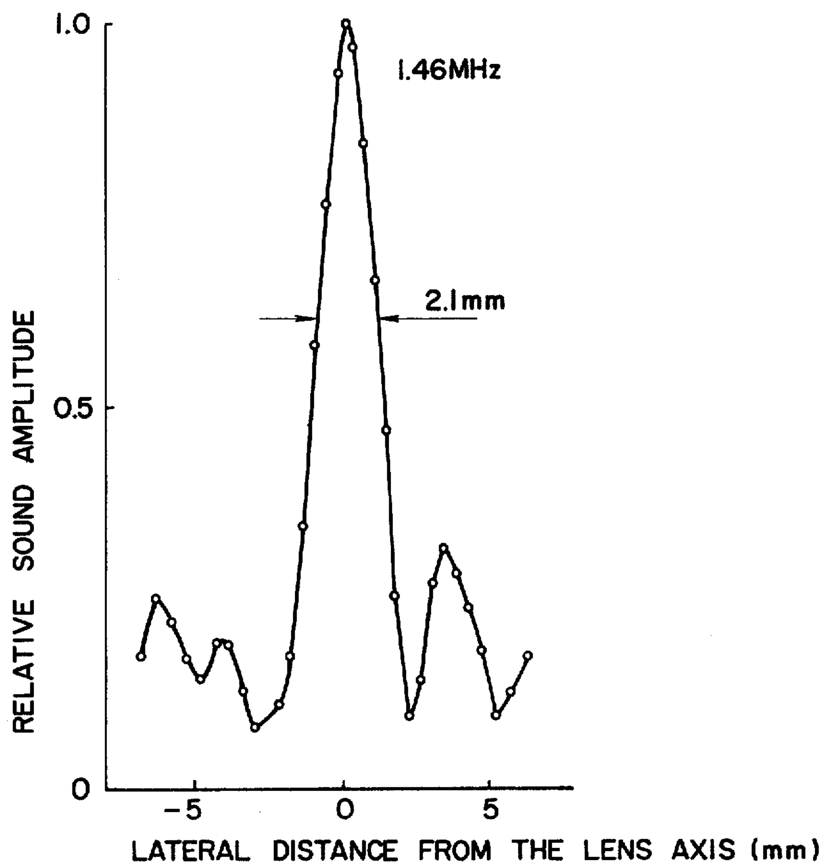
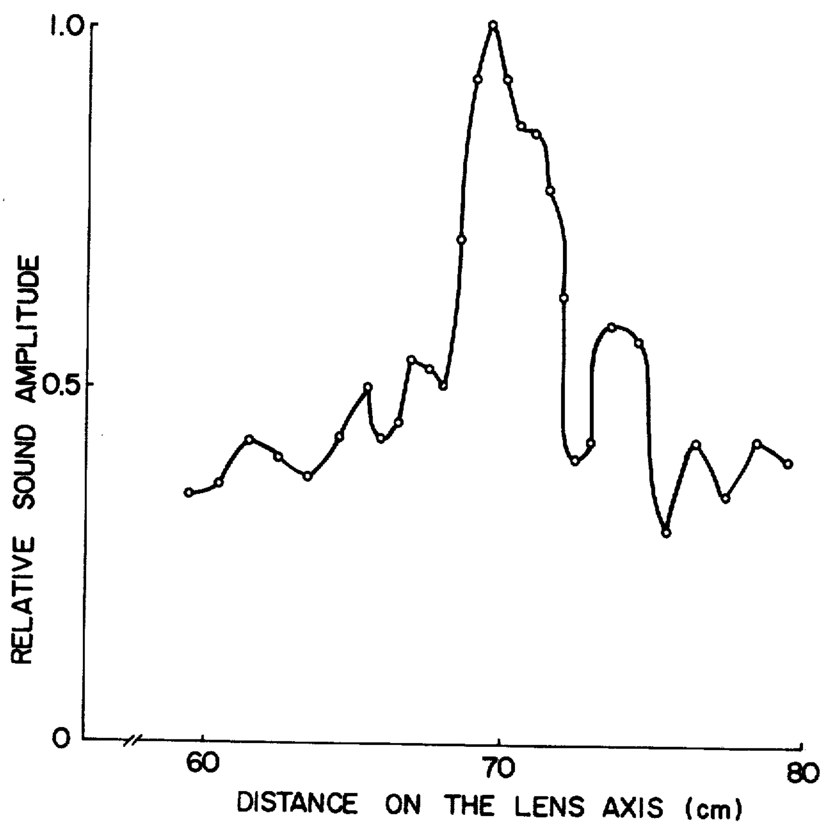

1.0
1.46MHz
2.1mm
0.5
0
RELATIVE SOUND AMPLITUDE
-5
0
5
LATERAL DISTANCE FROM THE LENS AXIS (mm)

FIG. 8


1.0
0.5
0
RELATIVE SOUND AMPLITUDE
60
70
80
DISTANCE ON THE LENS AXIS (cm)

ACOUSTIC LENS

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to an acoustic lens, and more particularly to a device which refracts sound waves and which has a converging action with respect to the sound waves.

2. Description of the Prior Art

In order to obtain the image of an object in, for example, muddy water, an optical device is substantially useless. An ultrasonic image pickup device is known in which, for that reason, the object image is produced by utilizing sound waves. The device is constructed such that the object is scanned with ultrasonic waves having a fixed sound wave beam width and that the object image is obtained from reflected sound waves from the particular object. In order to enhance the resolution of the image with such a device, the width of the scanning sound wave beam must be small. With a sound wave radiator itself, however, it is impossible to create a sound wave beam having a small beam width and having a fixed intensity.

Accordingly, such a prior-art device employs a method in which the sound wave beam is converged by an acoustic lens incorporated into a sound wave beam passage.

Since, however, the acoustic lens generally has a large aperture as compared with an optical lens and has a curved lens surface formed of a single curved surface, the thickness of the lens at the peripheral part thereof is large. Moreover, since the angle of incidence at the refracting curved surface is large, the effective diameter of the lens is markedly limited. At smaller focal lengths this tendency is more marked.

The F-value representative of the quality of a lens, that is, (focal length)/(effective lens diameter), is, accordingly, limited to approximately 2.5 at a minimum. For example, for converging a sound wave beam of a width of 50 cm by means of an acoustic lens of a width (diameter) of 50 cm, the effective beam width which contributes to the convergence (which may be considered the effective diameter of the lens) becomes 20 cm, and the sound wave beam is not efficiently utilized. Consequently, where the prior-art acoustic lens has a focal length approximately equal to the lens diameter, its effective diameter becomes small, and it cannot enhance the F-value or make the F-value small.

SUMMARY OF THE INVENTION

It is, accordingly, an object of the present invention to provide an efficient acoustic lens.

Another object of the present invention is to provide an acoustic lens having a small F-value.

Still another object of the present invention is to provide, in a comparatively simple structure, an acoustic lens which has an effective lens diameter approximately equal to its focal length.

In order to accomplish these objects, according to the present invention, an acoustic lens is constituted of a plurality of lens blocks of differing refracting curved surfaces and arranged adjacent one another, and block lenses consituting the outer peripheral blocks (other than a central block) of the acoustic lens are made thin and are so constructed that the angles of incidence of sound waves on the lenses of the outer peripheral blocks may become small.

The above-mentioned and other objects and features of the present invention will become more apparent from the following description taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a side sectional view of a plano-concave solid lens which is a prior-art acoustic lens;

FIGS. **2** and **3** are perspective views each showing the external appearance of an acoustic lens according to the present invention;

FIG. **4** is a side sectional view taken along a line IV—IV in FIG. **2** and for explaining the principle of the present invention;

FIG. **5** is a schematic diagram showing a part of FIG. **4** on enlarged scale for explaining the design of the embodiment of the present invention;

FIG. **6** is a diagram showing the aspect of the measurement of the converging characteristic of the acoustic lens according to the present invention; and

FIGS. **7** and **8** are graphs showing measured results of the converging characteristic of the acoustic lens according to the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Shown in FIG. **1** is an example of prior-art acoustic lens **1**, which is so formed that a surface **1** on the incidence side of sound waves is plane, while a surface **3** on the emergence side is arcuate.

Letting L denote the radius of curvature of the emergence side surface which is a refracting surface, n denote the refractive index of the material of the lens, and f denote the focal length of the lens, the following equation (1) holds:

$$L = (1 - n).f \qquad (1)$$

If the material of the lens **1** is an acrylic resin, the refractive index of the resin relative to water is $n = 0.54$. Assuming that the focal length of the acoustic lens is $f = 70$ cm, the radius of curvature L becomes 32 cm from Eq. (1). From these values, the F-value becomes 1.1. As is apparent from FIG. **1**, however, the thickness of the peripheral part of the lens **1** in the direction of the sound wave beam is remarkably large. Furthermore, the angle of incidence i is large and the angle of emergence r is small at the refracting curved surface at the peripheral part. The transmission factor of the sound wave R at the peripheral part of the lens is, accordingly, lowered conspicuously, so that the effective diameter of the lens becomes small.

FIG. **2** is a perspective view of an embodiment of the acoustic lens according to the present invention. The embodiment is a composite lens of the cylindrical type. FIG. **3** is a perspective view, partially in section, showing another embodiment of the acoustic lens according to the present invention. The embodiment is a composite lens of the circular type.

As is illustrated in the embodiments, the acoustic lens according to the present invention is formed at the outer periphery of a central lens block **1 — 1** with a plurality of lens blocks **1 - 2** and **1 - 3** which are adjacent to the central block and which are plane. In FIGS. **2** and **3**, an arrow as a symbol R indicates a sound wave. In accordance with the present invention, the thicknesses of the peripheral lens blocks in the propagating direction of the sound wave are remarkably reduced, and the transmission factor of a sound wave in the lens is enhanced.

FIG. 4 illustrates a section taken along a line IV—IV in FIG. 2, which section is the same as a section passing through the center of the circle in FIG. 3. Referring to FIG. 4, description will now be made of the function of the acoustic lens of the present invention.

In the figure, **1 - 1, 1 - 2** and **1 - 3** designate acoustic lens blocks. **2 - 1, 2 - 2** and **2 - 3** indicate sound-wave incidence surfaces of the acoustic lens blocks, while **3 - 1, 3 - 2** and **3 - 3** denote sound-wave emergence surfaces or refracting curved surfaces thereof. Reference numeral **4** represents the axis of the composite acoustic lens, and **4 - 1** and **4 - 2** the axes of the acoustic lens blocks **1 - 2** and **1 - 3** respectively. R_1, R_2 and R_3 designate incident sound-wave beams respectively corresponding to the acoustic lens blocks **1 - 1, 1 - 2** and **1 - 3**, while R_1', R_2' and R_3' denote emergent sound waves respectively corresponding to the aforesaid acoustic lens blocks. Shown at **0** is the focus of the lens. As is illustrated in FIG. 4, according to the embodiment, the lenses of the peripheral lens blocks **1 - 2** and **1 - 3** are made thin, and are so constructed that the planes **2 - 2** and **2 - 3** thereof on the incident side are respectively inclined to the incident waves R_2 and R_3.

Among the sound wave beams incident in parallel with the axis **4** of the lens, the sound wave beam R_1 incident on the central lens block **1 - 1** is not refracted at the incidence surface **2 - 1** of the lens as it enters orthogonally thereto, and it is refracted at the emergence surface **3 - 1**, to converge at the focus **0**. The sound wave beam R_2 incident on the lens block **1 - 2** is refracted at the incidence surface **2 - 2**, it is further refracted at the emergence surface **3 - 2**, and it converges at the focus **0**. Similarly, the sound wave beam R_3 incident on the lens block **1 - 3** is refracted at the surfaces **2 - 3** and **3 - 3**, to converge at the focus **0**.

In order that all the sound wave beams R_1, R_2 and R_3 having passed through the respective lens blocks **1 -, 1 - 2** and **1 - 3** may converge at the focus **0** in this manner, the incidence surfaces **2 - 2** and **2 - 3** of the respective lens blocks **1 - 2** and **1 - 3** are provided at angles so that the sound wave beams refracted at these surfaces may become, within the corresponding lens blocks, parallel to the axis **4 - 1** connecting the joint point of the emergence surfaces **3 - 1** and **3 - 2** and the focus **0** and to the axis **4 - 2** connecting the joint point of the emergence surfaces **3 - 3** and **3 - 2** and the focus **0**, and also, the emergence surfaces **3 - 2** and **3 - 3** of the respective lens blocks **1 - 2** and **1 - 3** are so set as to have their foci at the point **0**.

The design of each lens block will now be described more in detail.

FIG. 5 shows the lens blocks in FIG. **4** on an enlarged scale.

In the embodiment illustrated herein, the emergence surface or refracting surface is elliptical. It is known that, letting a be the major axis, b be the minor axis and e be the eccentricity of an ellipse and letting f be the focus of an elliptic plane, the relations of the following equations hold:

$$a = \frac{f}{1+e} \qquad (2)$$

-Continued

$$b = f \sqrt{\frac{1-e}{1+e}} \qquad (3)$$

$$e = \frac{n_1}{n_o} \qquad (4)$$

where n_1 denotes the refractive index of the material of a lens, and n_o that of a medium (which may be considered water).

In the case of the ellipse, the aberration is small. If some aberration is allowed, the curved surface may be circular. In this case, the focal length f and the radius of curvature R of the circle have the following relation:

$$f = \frac{n_o}{(n_o - n_1)R} \qquad (5)$$

Hereunder, however, description will be made of the case where the refracting curved surface is elliptical.

Now, letting f_0 be the focal length of the lens block **1 - 1**, d_0 be the minimum thickness of the lens and h_0 be the width of the lens, the depth g_0 at the central part of the lens is expressed by:

$$g_0 = f_o - a_o \left(1 - \frac{\sqrt{b_o^2 - h_o^2}}{b_o}\right) \qquad (6)$$

where a_0 and b_0 denote the lengths of the major axis and the minor axis of the refracting surface of the lens block **1 - 1**, respectively.

The maximum thickness T_0 of the lens block **1 - 1** is given by:

$$T_0 = d_0 + g_0 \qquad (7)$$

As regards the lens block **1 - 2**, the focal length f_1 is given by:

$$f_1 = \sqrt{h_0^2 + (f_0 - g_0)^2} \qquad (8)$$

The depth g_1 of the lens is given by:

$$g_1 = f_o - g_o + a_1 \left(1 - \frac{\sqrt{b_1^2 - (h_1 + h_o)^2}}{b_1}\right) \qquad (9)$$

where h_1 denotes the lens width, and a_1 and b_1 the lengths of the major axis and the minor axis of the lens block **1 - 2** respectively.

Letting θ_1 be the angle of inclination of the incidence surface **2 - 2** and d_1 be the minimum thickness of the lens, the maximum thickness T_1 of the lens block **1 - 2** is given by:

$$T_1 = h_1 . \tan \theta_1 + d_1 + g_1 \qquad (10)$$

The angle of incidence 0_1 of the incident sound wave R_2 is given from Snell's formula by:

$$n_o . \sin \theta_1 = n_1 . \sin (\theta_1 + \theta_1') \qquad (11)$$

Accordingly,

$$\tan \theta_1 = \frac{\sin \theta_1'}{\frac{n_o}{n_1} - \cos \theta_1'}$$

-Continued

$$\sin \theta_{1'} = \frac{h_0}{f_1}, \quad (12)$$

$$\cos \theta_{1'} = \frac{f_0 - g_0}{f_1}$$

As regards the lens block **1 - 3**, the quantities are similarly determined.

On the basis of the various equations, there will now be explained an example of the cylindrical type lens of the present invention as shown in FIG. **2.**

In this lens, the focal length is $f_0 = 70$ cm, the diameter is $h_0 + h_1 + h_2 = 45.2$ cm, the the height (the length of the cylinder) is 25 cm.

The material of the lens is polymethyl methacrylate the refractive index n, of which is $n_1 = 0.54$ at a temperature of 20°C. The refractive index of water is $n_0 = 1$.

The physical configurations of the respective lens blocks are as in the following table:

Table 1

	Lens Block 1 – 1	Lens Block 1 – 2	Lens Block 1 – 3
Focal length (f)	70.00	68.42	68.04
Major axis of ellipse (a)	45.45	44.43	44.18
Minor axis of ellipse (b)	38.26	37.49	37.19
Minimum lens thickness (d)	1.00	1.00	0.93
Maximum lens thickness (T)	3.92	3.38	3.77
Diameter of lens (h)	13.50	5.22	3.93
Inclination of incidence surface (θ)	0	12°45′23″	17°10′22″

The units of the quantities except θ are cm.

The F-value of the acoustic lens according to the above embodiment becomes 1.5. As is apparent from the embodiment, the thicknesses of the lenses at the peripheral parts become less than 4 cm. As compared with the acoustic lens in FIG. **1** having the same diameter (approximately 10 cm thick at the peripheral part), the embodiment can be made remarkably thin at the peripheral parts and can have the sound-wave beam loss reduced. That is, the transmission factor of the sound wave beam is enhanced.

Regarding the phases of the sound wave beams from the respective lens blocks at the focal position, since the sound wave beams have long wavelengths, the phases can be made coincident with respect to the wavelength of a specific sound wave in use by adjusting the thicknesses of the lens blocks.

The acoustic lens of the foregoing embodiment is designed for sound waves at 1.46 MHz (having a wavelength of 1.02 mm in the water). With the embodiment, the phases of the respective sound wave beams at the focal position are substantially coincident.

FIG. **6** shows the aspect of actual measurement for measuring the converging characteristic of the acoustic lens according to the present invention.

In the figure, reference numeral **5** designates a transducer for generating a sound wave beam. It is constructed by disposing a number of piezo-electric elements in an array, has a size of 50×1 cm^2, and radiates plane waves. The frequency of the sound waves of the transducer is 1.46 MHz (the wavelength in the water is 1.02 mm), while the width D of the sound wave beam is 43.2 cm. The transducer is inclined since the radiating direction slants in dependence on the frequency. Reference numeral **1** indicates the acoustic lens according to the present invention, which has substantially the same construction as in Table 1 and which is arranged at a place approximately 50 cm distant from the transducer **5.** Arrows around the focal position **0** in the figure indicate the directions of scanning by the sound wave beam.

FIGS. **7** and **8** represent a sound pressure distribution in the lateral direction and a sound pressure distribution along the lens axis in the vicinity of the focus as actually measured by the method illustrated in FIG. **6,** respectively. In the figures, the abscissas represent distance, while the ordinates represent the relative sound amplitude.

From the inventor's experiments, as explained above, it is apparent that the acoustic lens according to the present invention exhibits reliable converging characteristics.

While the present invention has thus far been described in detail in connection with the preferred embodiments, it is to be understood that the present invention is not restricted thereto. The material, configuration, etc. can be variously altered within the spirit of the present invention.

What I claim is:

1. An acoustic lens which has an axis and focal length comprising:

1. a central lens block, the lens axis and the focal length of which are coincident with those of said acoustic lens; and
2. a plurality of peripheral lens blocks which are disposed at the outer periphery of the central lens block in the form of planes adjacent said central lens, and in which incidence surfaces of the lens blocks are formed of plane faces inclined relative to the axis of said acoustic lens so that sound waves incident on said lens blocks will emerge from respective emergence surfaces of said blocks in a direction along lines connecting their respective points of emergence on the focal point side, and the focus of said acoustic lens, while said emergence surfaces of said lens blocks are formed of curved surfaces by which incident sound waves converge at the focus of said acoustic lens.

2. An acoustic lens according to claim **1,** wherein the curved emergence surfaces of said block lenses are elliptical.

3. An acoustic lens according to claim **1,** wherein the thicknesses of said lens blocks along said lens axis are so set that differences among path lengths of said sound waves passing through said respective lens blocks may become substantially zero or an integral multiple of a prescribed acoustic wavelength.

4. An acoustic lens according to claim **1,** wherein said block lenses are cylindrical, and said lens blocks are constructed adjacent one another so that the axes of the respective cylinders lie in a plane orthogonal to said axis of said acoustic lens and are parallel to one another.

5. An acoustic lens comprising:

a first lens element having a planar surface on one side thereof and a concave surface on the opposite side thereof and a focal point at a prescribed distance from said concave surface along an axis, passing through said element, which is perpendicular to said planar surface;

a second lens element which annularly surrounds and is adjacent the outer periphery of said first lens element, having a surface on one side thereof inclined relative to said planar surface of said first lens element, and a concave surface on the opposite side thereof facing said focal point; and

wherein the angle of inclination of the inclined surface of said second lens element relative to said planar surface of said first lens element and the curvature of the concave surface of said second lens are such that acoustic waves impingent upon said inclined surface of said second lens element converge at said focal point.

6. An acoustic lens according to claim **5**, further including a third lens element which annularly surrounds and is adjacent the outer periphery of said second lens element, having a surface on one side thereof inclined relative to said planar surface of said first lens element, and a concave surface on the opposite side thereof facing said focal point; and

wherein the angle of inclination of the inclined surface of said third lens element relative to said planar surface of said first lens element and the curvature of the concave surface of said third lens element are such that acoustic waves impingent upon said inclined surface of said third lens element converge at said focal point.

7. An acoustic lens according to claim **5**, wherein the concave surfaces of said first and second lens elements intersect each other.

8. An acoustic lens according to claim **6**, wherein the concave surfaces of said first and second lens elements and the concave surfaces of said second and third lens elements, respectively, intersect each other.

9. An acoustic lens according to claim **7**, wherein the inclined surface of said second lens element intersects a side surface of said first lens element at a prescribed distance from the point of intersection of the concave surfaces of said first and second lens elements and a specified distance from the planar surface of said first lens element.

10. An acoustic lens according to claim **8**, wherein the inclined surface of said second lens element intersects a side surface of said first lens element at a prescribed distance from the point of intersection of the concave surfaces of said first and second lens elements and a specified distance from the planar surface of said first lens element.

11. An acoustic lens according to claim **10**, wherein the inclined surface of said third lens element intersects a side surface of said second lens element at a prescribed distance from the point of intersection of the concave surfaces of said second and third lens elements and a specified distance from the inclined surface of said second lens element.

12. An acoustic lens according to claim **5**, wherein the concave surfaces of said first and second lens elements are elliptically shaped.

13. An acoustic lens according to claim **6**, wherein the concave surfaces of said first, second and third lens elements are elliptically shaped.

14. An acoustic lens which has an axis and a focal length comprising:

1. a central lens block, the lens axis and the focal length of which are coincident with those of the acoustic lens;
2. a plurality of annular concentric peripheral lens blocks which are disposed at the outer periphery of the central lens block having incidence surfaces, the cross-sections of which through a plane in which the lens axis lies form lines inclined relative to the lens axis, so that sound waves incident of said lens blocks will emerge from respective emergence surfaces of said blocks in a direction along lines connecting their points of emergence on the focal point side, and the focus of said acoustic lens, while said emergence surfaces of said lens blocks are formed of curved surfaces by which the incident sound waves converge at said focus of said acoustic lens.

15. An acoustic lens comprising:

a first lens element having a planar surface on one side thereof and a concave surface on the opposite side thereof and a focal point at a prescribed distance from said concave surface along an axis, passing through said element, which is perpendicular to said planar surface;

a second lens element which is disposed adjacent the outer periphery of said first lens element, having a surface on one side thereof inclined relative to said planar surface of said first lens element, and a concave surface on the opposite side thereof facing said focal point; and

wherein the angle of inclination of the inclined surface of said second lens element relative to said planar surface of said first lens element and the curvature of the concave surface of said second lens element are such that acoustic waves impingent upon said inclined surface of said second lens element converge at said focal point.

16. An acoustic lens according to claim **15**, further including a third lens element which is disposed adjacent the outer periphery of said second lens element, having a surface on one side thereof inclined relative to said planar surface of said first lens element, and a concave surface on the opposite side thereof facing said focal point; and

wherein the angle of inclination of the inclined surface of said third lens element relative to said planar surface of said first lens element and the curvature of the concave surface of said third lens element are such that acoustic waves impingent upon the inclined surface of said third lens element converge at said focal point.

* * * * *