July 23, 1946. W. P. MASON 2,404,391

PRISMATIC AND HIGH POWER COMPRESSIONAL-WAVE RADIATOR AND RECEIVER

Filed Feb. 19, 1942 4 Sheets-Sheet 1

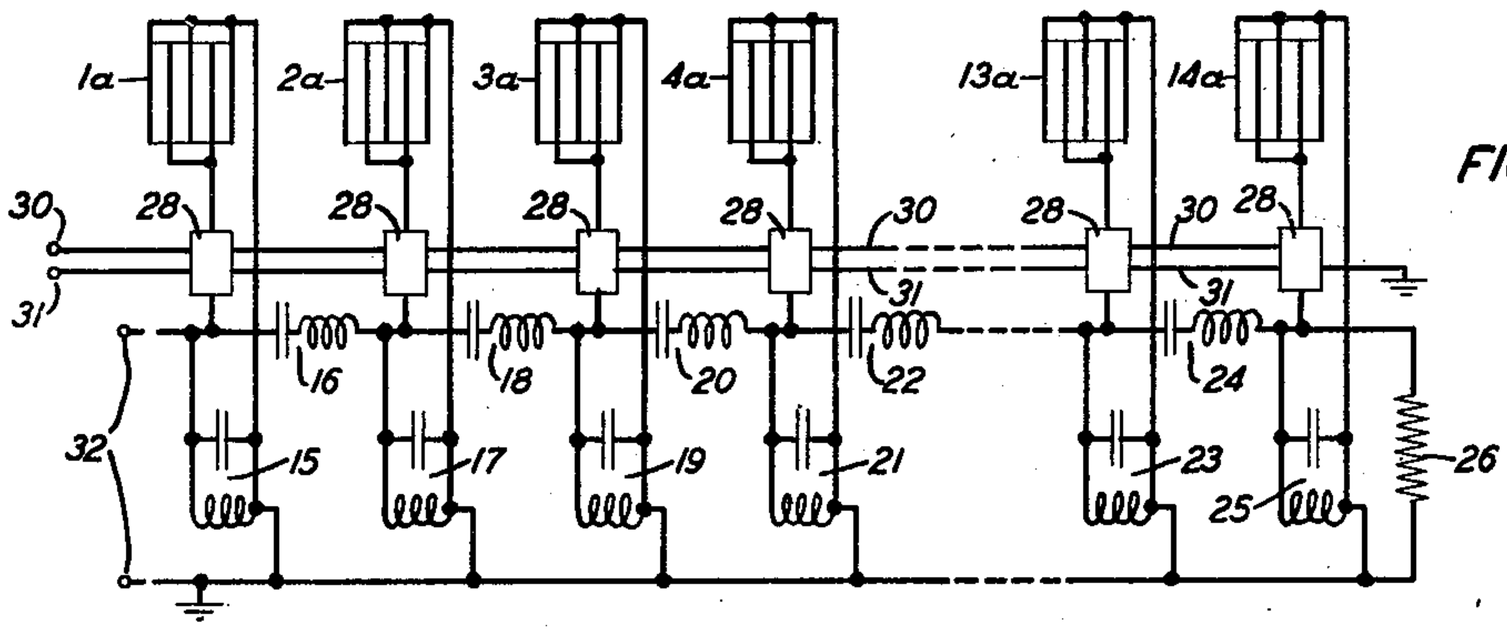



FIG. 1A

FIG. 11

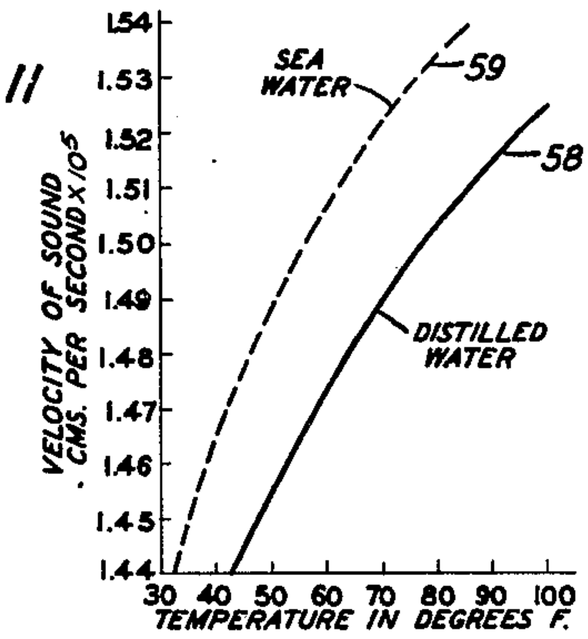



FIG. 1B

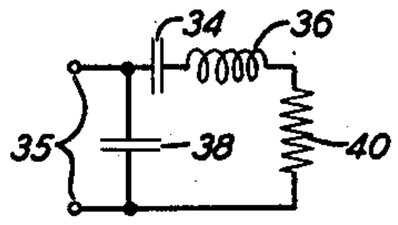
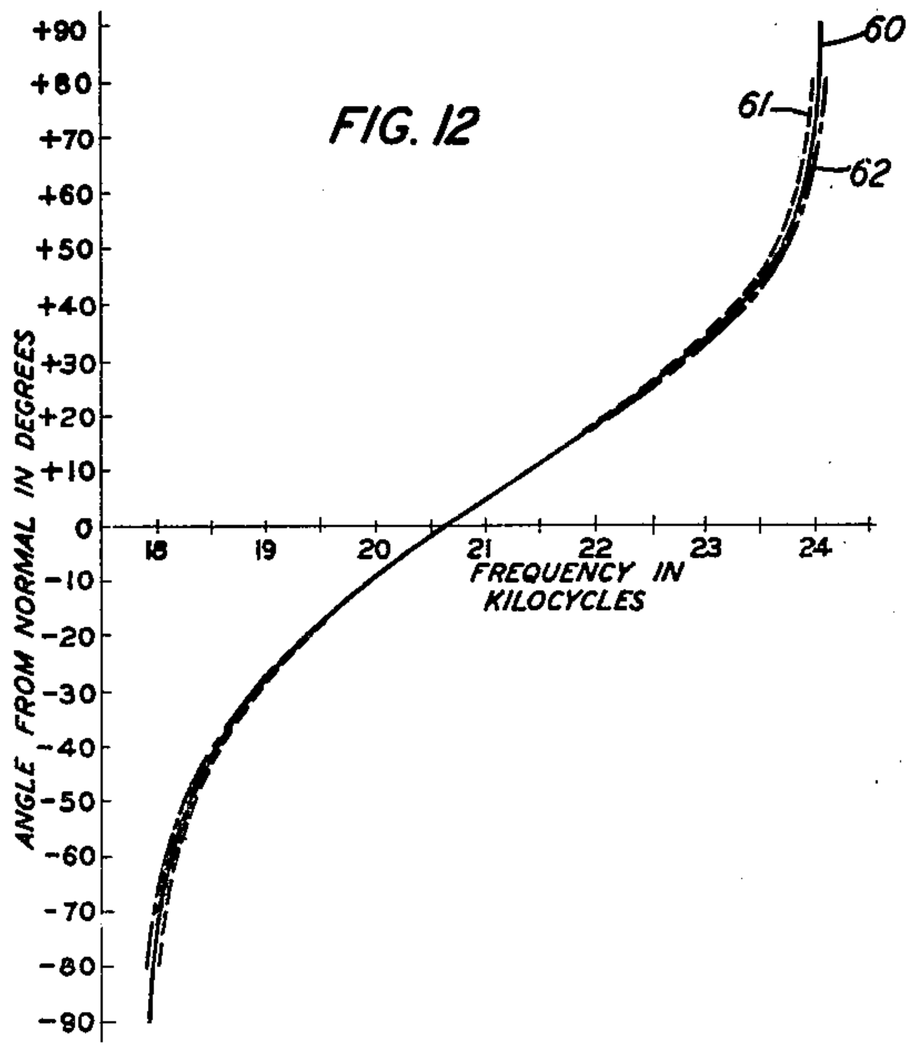



FIG. 12




INVENTOR
W. P. MASON
BY H. O. Wright
ATTORNEY

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PRISMATIC AND HIGH POWER COMPRESSIONAL-WAVE RADIATOR AND RECEIVER

Filed Feb. 19, 1942 4 Sheets-Sheet 2

FIG. 2

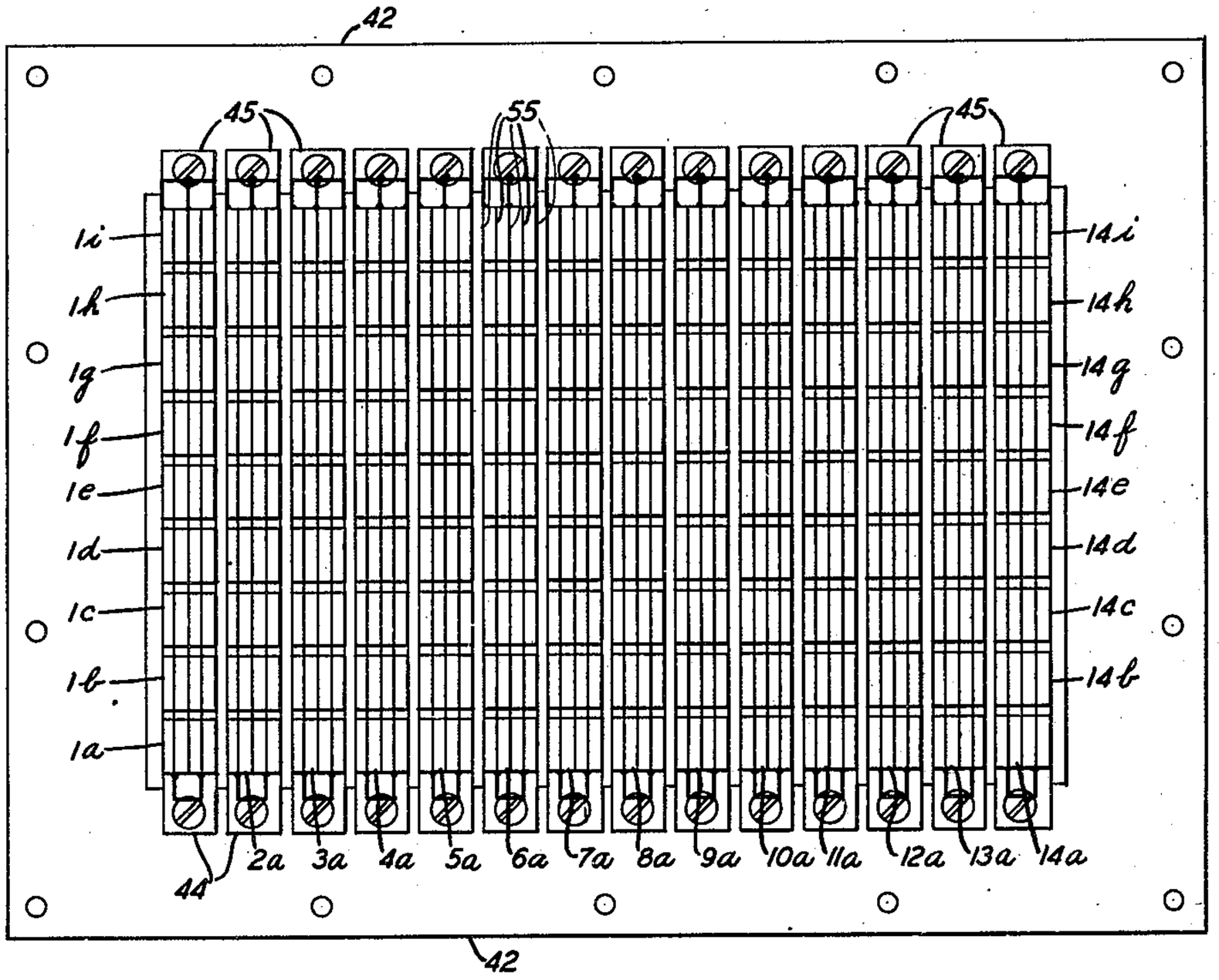
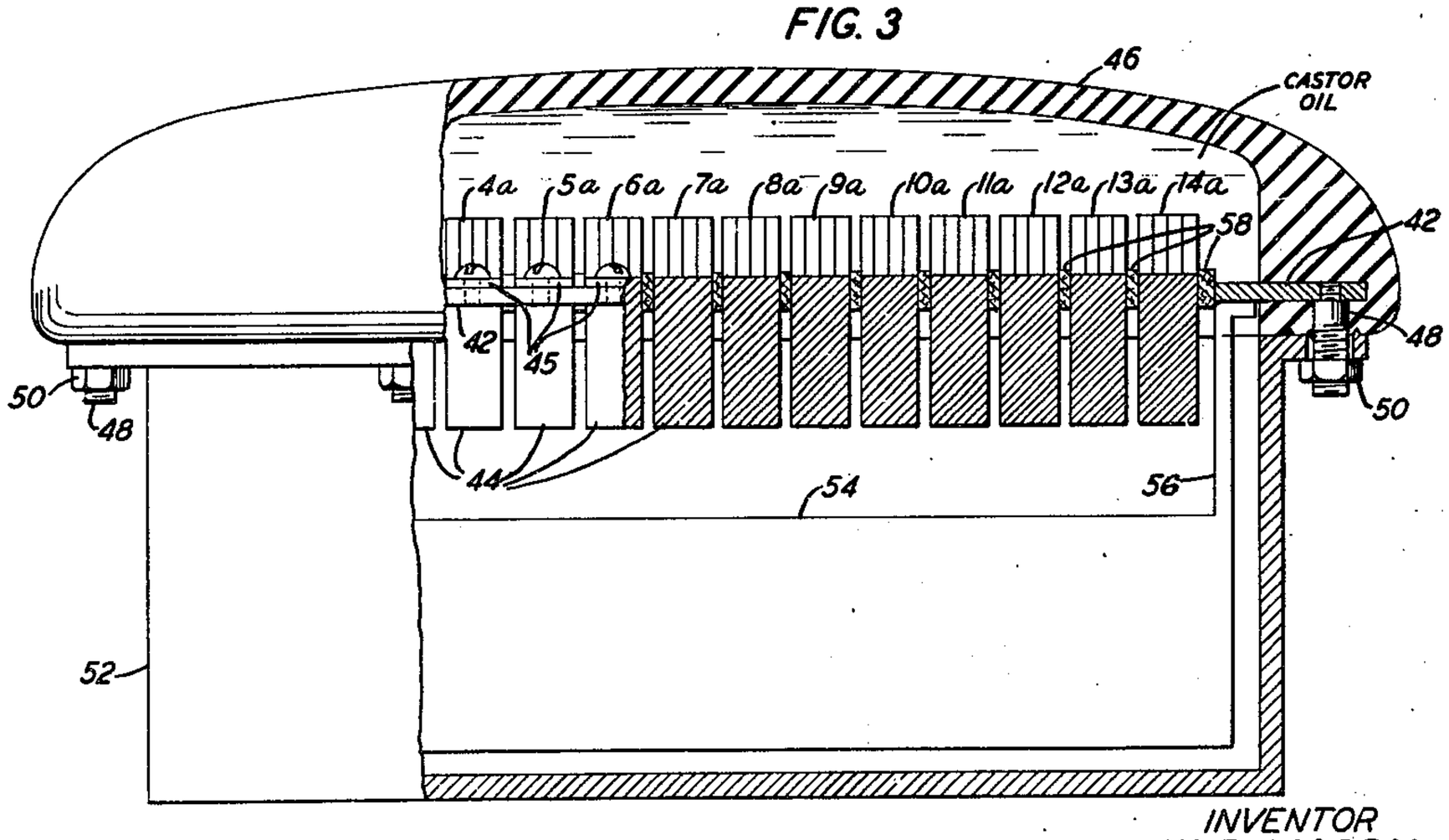



FIG. 3




INVENTOR
W. P. MASON
BY H. O. Wright
ATTORNEY

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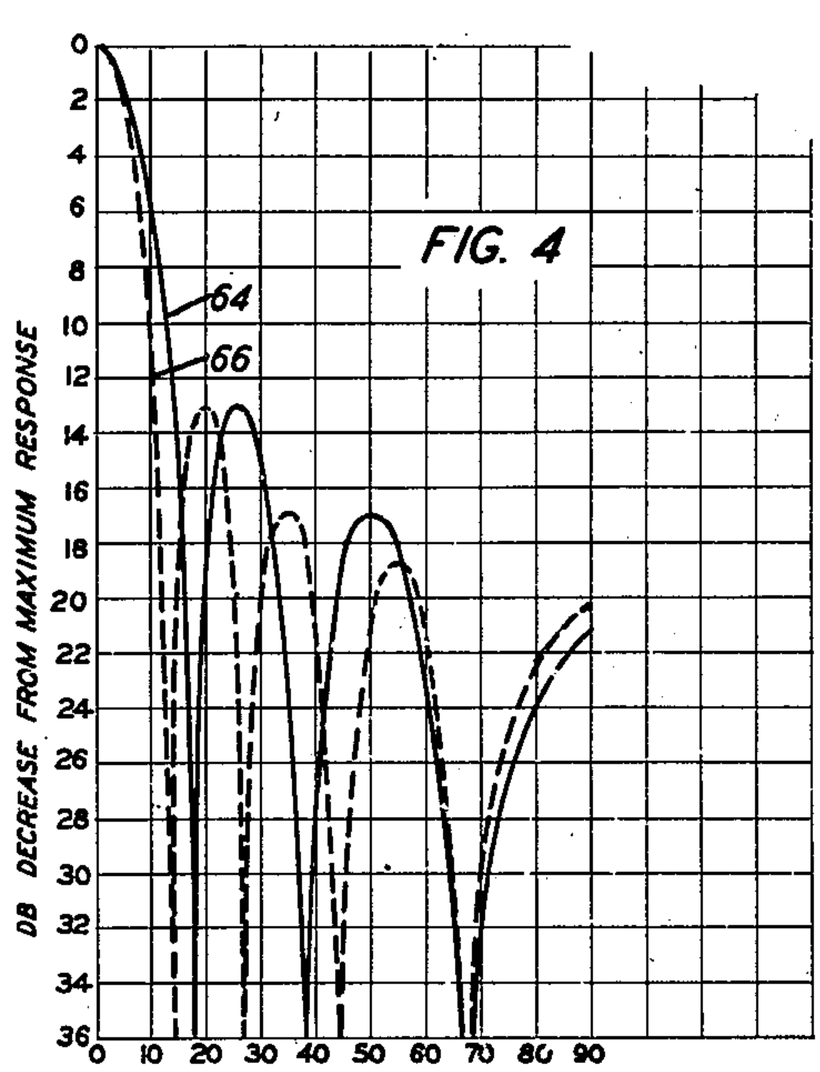
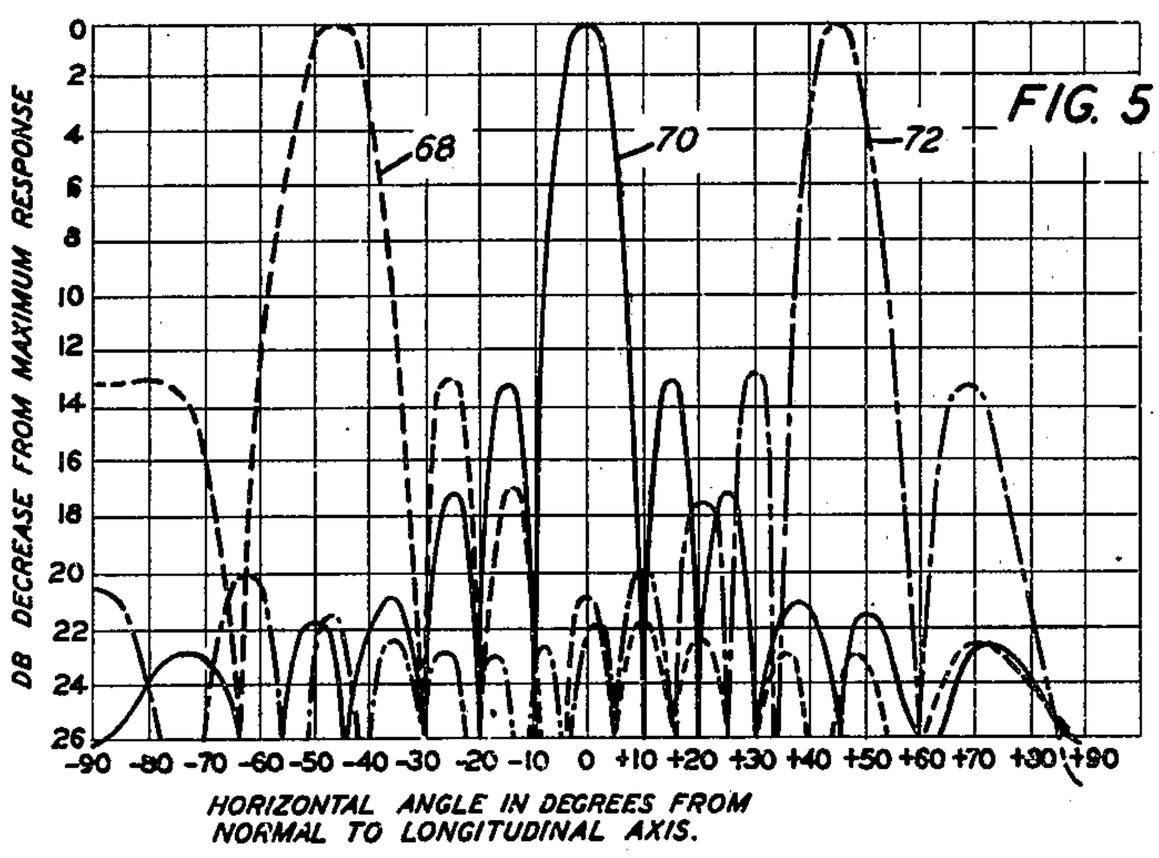
PRISMATIC AND HIGH POWER COMPRESSIONAL-WAVE RADIATOR AND RECEIVER

Filed Feb. 19, 1942 4 Sheets-Sheet 3




INVENTOR
W. P. MASON
BY H. O. Wright
ATTORNEY

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PRISMATIC AND HIGH POWER COMPRESSIONAL-WAVE RADIATOR AND RECEIVER

Filed Feb. 19, 1942 4 Sheets-Sheet 4

FIG. 6

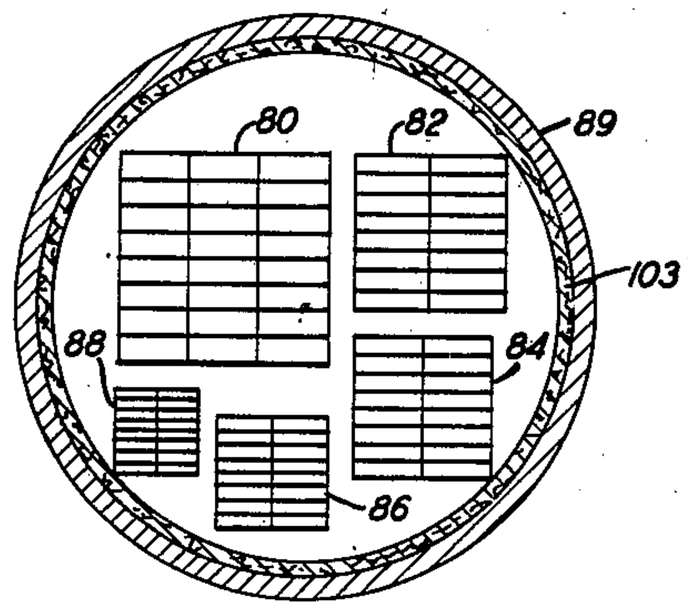



FIG. 7

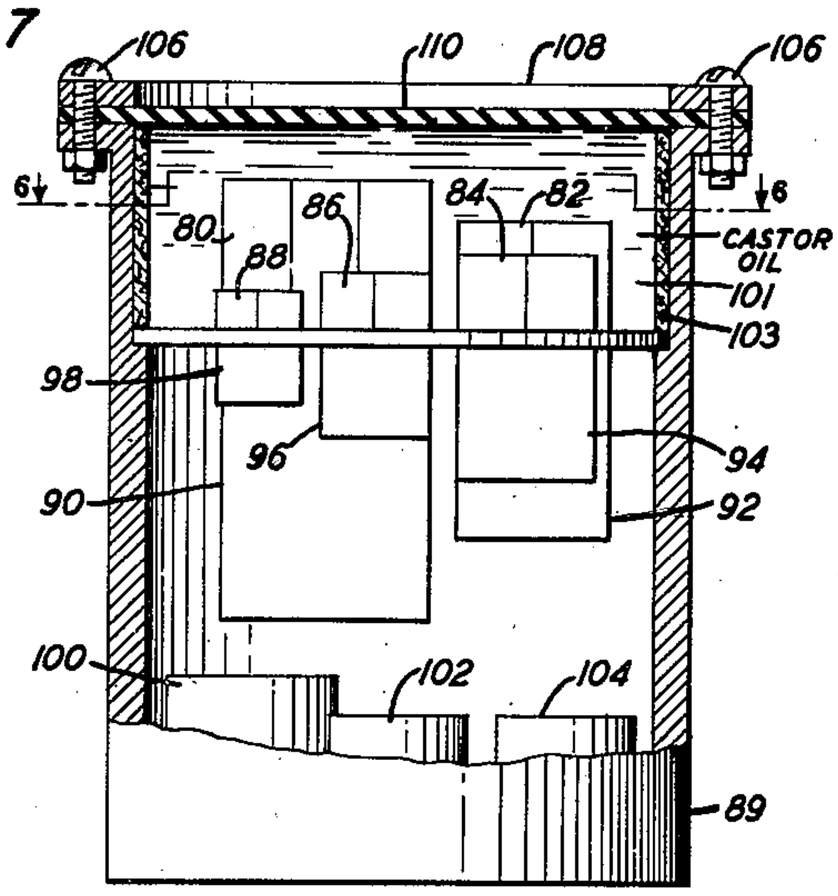



FIG. 8

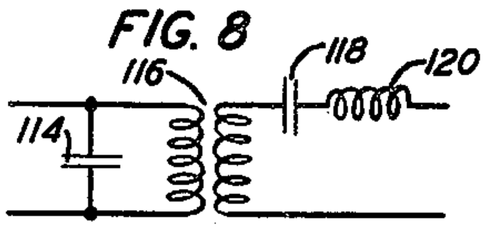



FIG. 9

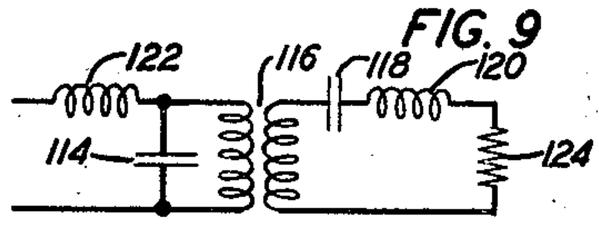
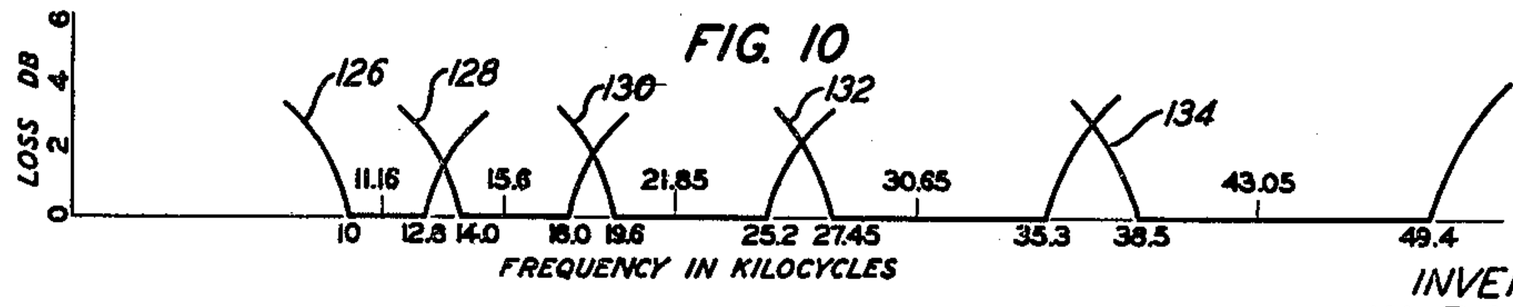



FIG. 10




INVENTOR
W. P. MASON
BY H. O. Wright
ATTORNEY

Patented July 23, 1946 2,404,391

# UNITED STATES PATENT OFFICE

2,404,391

## PRISMATIC AND HIGH POWER COMPRESSIONAL-WAVE RADIATOR AND RECEIVER

Warren P. Mason, West Orange, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application February 19, 1942, Serial No. 431,558

6 Claims. (Cl. 177—386)

1

This invention relates to multiunit radiating and receiving devices and to high power compressional wave radiating devices. In the hereinafter-described preferred embodiments, illustrative of the principles thereof, it relates particularly to radiating and receiving devices employing a large number of piezoelectric crystals which are capable of radiating high power compressional energy waves and to compressional wave energy radiators and receivers which have "prismatic" properties.

By way of definition, in the present specification, a prismatic device, for other than light energy waves should be understood to be a device which in transmitting a wave comprising energy of numerous frequencies within a particular frequency spectrum, will spread the frequency spectrum by imparting a change in direction, differing for each frequency, to the several frequencies of the spectrum or which in receiving energy will respond to the several frequencies of the spectrum only when they approach the device at particular respective angles, differing for each frequency.

This application is also directed to the discovery that if a piezoelectric crystal be immersed in a fluid of relatively great viscosity the power limiting phenomena known as "cavitation" will not become troublesome until substantially higher power levels have been reached than for crystals immersed in fluids of relatively low viscosity.

"Cavitation" comprises the formation of bubbles on the surface of the crystal and is accompanied by a substantial increase in the dissipation of power at the surface of the crystal. When the point at which cavitation occurs has been reached, further increases of input power result in increased dissipation, deterioration and the ultimate destruction of the crystal, with relatively small increase in power output. Cavitation is therefore definitely a serious limitation in the operation of high power crystal radiators. For other types of vibrating radiators also, such as magnetostrictive or electromagnetic vibrators cavitation will seriously impair the efficiency with which compressional wave energy may be radiated and the use of a highly viscous liquid to increase the power level at which cavitation takes place is extremely advantageous.

As pointed out in my copending application Serial No. 413,429, filed October 3, 1941, entitled "Compressional wave radiators and receivers," the heating of Rochelle salt crystals from any cause to a temperature of 40° C. or higher is most objectionable since this reduces the leakage resistance of the crystals to such a low value as to

2

become an appreciable factor causing further heating, with consequent deterioration and ultimate destruction of the crystals.

The prismatic characteristics of the devices of the present invention are, of course, similar to those of the devices of my copending application entitled "Pipe antennas and prisms," filed March 1, 1941, Serial No. 381,236.

Principal objects of the invention are to provide high power compressional wave piezoelectric radiators, prismatic compressional wave radiators and receivers of a novel type and wide band radiating and receiving composite compressional wave devices.

Another important object is to reduce the deleterious effects of cavitation in the use of piezoelectric crystals and other electromechanical vibrating devices employed in compressional wave systems.

A further object is to provide suitable impedance matching media and power distributing media between the array of crystals of a multicrystal piezoelectric radiator and sea water.

Other and further objects will become apparent during the course of the following description and from the appended claims.

The character and features of the invention will be more readily understood from the following description of particular illustrative embodiments, taken in conjunction with the accompanying drawings, in which:

Fig. 1A illustrates in electrical schematic and diagrammatic form an array of piezoelectric crystals in combination with a multisection electric wave filter;

Fig. 1B shows in simplified electrical schematic form the equivalent electrical circuit of a plurality of piezoelectric crystals employed as a compressional wave energy radiator or receiver;

Figs. 2 and 3 show the outstanding mechanical features of an illustrative embodiment of a multicrystal piezoelectric compressional wave high power radiator of the invention;

Figs. 4 and 5 illustrate the vertical and horizontal directive characteristics of the device of Figs. 2 and 3;

Figs. 6 and 7 are top and side cross-sectional views of an assembly of five units providing a broad band compressional wave piezoelectric receiver or radiator of the invention;

Figs. 8 and 9 are electrical schematic diagrams employed in explaining the character and use of the device illustrated in Figs. 6 and 7;

Fig. 10 illustrates the composite transmission characteristics of the five units of Figs. 6 and 7;

Fig. 11 illustrates the change in the velocity of sound with temperature for sea water and for distilled water; and

Fig. 12 illustrates the prismatic directive characteristics of a piezoelectric radiating or receiving array of the invention, such as is illustrated in Figs. 2 and 3.

In more detail in Fig. 1A a plurality of groups of four piezoelectric crystals in each group, namely, groups 1*a*, 2*a*, 3*a*, etc., are shown associated with a multisection band-pass electrical wave filter comprising shunt arms 15, 17, 19, etc., and series arms 16, 18, 20, etc. Successive groups of the crystals are connected electrically in shunt with successive shunt arms of the filter respectively, as shown in Fig. 1A. The right end of the filter is terminated in a resistive impedance 26 which is appropriately related to the impedance of the adjacent filter section over the transmitting band of the latter as will be described hereinafter. If the arrangement is to be used as a radiator, electrical energy comprising frequencies within the pass-band of the filter is introduced through the terminals 32 at the left end of the filter. When used as a receiver the compressional wave energy is converted by the crystals into electrical energy which may be drawn from terminals 32.

The crystal groups 1*a*, 2*a*, 3*a*, etc. are preferably aligned with a distance between centers which is less than half the wave-length of the highest frequency to be radiated or received. This is necessary in order that a single direction of transmission or reception will obtain for each frequency. As wave-length is the quotient of velocity of propagation divided by the frequency the nature of the propagating medium must be taken into consideration. Fig. 11 shows the variation of sound velocity with temperature for sea water, curve 59, and distilled water, curve 58, respectively.

In general, the directivity of such a device for both radiation and reception in any particular plane will vary with the dimension of the device parallel to that plane. For sharp directivity a dimension in the order of at least five wavelengths of the lowest frequency employed is desirable.

The phase shift of an electrical wave filter section of the type employed in the filter illustrated in Fig. 1A is well known in the art. For example, see the text-book "Transmission Networks and Wave Filters" by T. E. Shea, published by D. Van Nostrand Company, Inc., New York, 1929, pages 215 and 216, Figs. 106 and 107. It varies from $-\pi$ at the lower cut-off to $+\pi$ at the upper cut-off, passing through zero at the mid-frequency of its transmission band. Thus any desired phase shift, between the above-stated limits, per filter section can be obtained by selecting the frequency in the pass-band corresponding to the desired phase shift. Of course, for each particular phase shift per section the array of crystal groups will transmit or receive energy at a particular angle since each crystal group differs in phase from adjacent groups by the phase shift of one filter section.

If two or more different frequencies, within the pass-band of the filter sections, are introduced into the device of Fig. 1A, each frequency will be transmitted in a particular direction, different for each frequency, respectively, since the phase shift per filter section will be different for each frequency.

Conversely, for the reception of energy of a particular frequency within the pass-band of the filter sections the arrangement illustrated in Fig. 1A will respond with maximum efficiency only if the energy approaches from a particular angle which is dependent upon the phase shift per section of the wave filter at that frequency.



The arrangement of Fig. 1A, therefore, normally has "prismatic" properties as defined above.

Relay switches 28 are provided to operate on voltage placed on conductor 30 and to disconnect the ungrounded conductors of the crystal groups from their respective filter sections and to connect them to a common conductor 31 so that all crystal units may be operated in phase at all frequencies in the event that prismatic characteristics are not desired. Radiation will then be broadside or normal to the longitudinal axis of the array for all frequencies.

Figs. 2 and 3 show the salient mechanical design features of a device, the electrical schematic of which can be that shown in Fig. 1A. To permit the radiation of greater power, and to increase the vertical directivity characteristics of the device, each of the crystal groups 1*a*, 2*a*, 3*a*, etc. of Fig. 1A is further expanded by adding eight similar groups of four crystals each, connected electrically in parallel with the original group so that the complete radiator of Figs. 2 and 3 comprises fourteen vertical rows of crystal groups, each row comprising nine groups and each group comprising four crystals, i. e., thirty-six crystals per row and five hundred and four crystals for the complete radiator. The nine groups of each row, for example, groups 1*a* to 1*i*, inclusive, or 14*a* to 14*i*, inclusive, as shown in Fig. 2, can conveniently have common electrodes (55 of Fig. 2) running the entire length of the row. Five electrodes are, of course, required, one between each pair of adjacent crystals and one on the outer surface of the two outside crystals of each group. The electrodes 55 can be of metal foil and are cemented or otherwise attached to the adjacent crystal surfaces.

The groups of crystals of each row are in turn cemented to their respective mounting strips 45, a thin insulating spacer being interposed between the crystal groups and the metal mounting plate to afford high insulation resistance. Ceramic spacers of low dielectric constant and a cement also of low dielectric constant and unusually strong adhesive properties have been found most suitable for this purpose, since lower values of capacity to ground as well as higher breakdown voltages are thus obtained. These features are of especial importance for devices which are to radiate high power. The crystal groups are equally spaced along the mounting strip with a small interval between groups to afford appropriate directivity in the vertical plane as described hereinafter. The mounting strips 45 are screwed to a mounting plate 42, which is assembled, as shown in Fig. 3, to clamp the edges of a composition rubber cover 46 tightly against a casing 52 by means of bolts 48 and nuts 50. The composition rubber cover is preferably of a material recently developed by one or more of the large rubber manufacturers to have substantially the same velocity of propagation of compressional wave energy as sea water and thus to increase the efficiency of energy transfer to or from the water.

A multisection filter, such as is illustrated in the schematic diagram of Fig. 1A, is mounted in a case 54 attached to mounting plate 42 by brackets 56. As the successive rows of crystals are

directly shunted across successive shunt arms of the filter the effective electrical impedance of the rows of crystals and the distributed capacity in the wiring thereto should be taken into consideration in the filter design as an integral part of its associated filter arm impedance. The use of 45 degree Y-cut crystals again is very advantageous in this connection, since the capacity of such crystals varies very little with temperature changes and will not, therefore, appreciably impair the filter's characteristics with temperature changes normally encountered in submarine signaling. As a practical matter the provision of small trimming capacities whereby the resonance of the arms may be exactly adjusted after final assembly will be found advantageous.

Gaskets **58** of rubber or oil-proofed felt or the like are placed between the mounting strips **45** of adjacent rows and the space between the rubber cap and the crystals is filled with castor oil or some other highly viscous fluid, such as olive oil or linseed oil, which will eliminate cavitation at the power level to be employed and will serve to efficiently transmit compressional wave energy. The viscous fluid should be of such character that it can be dried conveniently to exclude moisture from the crystal surfaces.

The mounting strips **45** include a backing block of metal **44** for each group of crystals. The crystal groups are mechanically one-quarter wave-length high and the backing blocks are likewise mechanically one-quarter wave-length high, the difference in height between the crystals and the backing blocks arising from the difference in the velocity of propagation of compressional wave energy in the two materials. This type of mounting is discussed in detail in my above-mentioned copending application Serial No. 413,429 and its purpose is to produce a node of motion at the mounting strip **45** so that energy from the crystal groups in one row will not be transmitted to groups of adjacent rows or to the mounting plate **42** and casing **52**. If transmitted to adjacent rows it can impair or destroy the desired directive effects by introducing energy of other than the desired phase and if transmitted to the mounting plate and case it can result in substantial dissipation and in the radiation or reception of energy from the sides or rear of the device, thus again impairing the efficiency and the directive properties of the device. For a well balanced assembly in which the backing blocks and crystals are accurately proportioned the fourteen mounting strips **45** can be replaced by a single mounting plate and the backing blocks **44** for each row can be replaced by a single bar running the length of the row, thus eliminating gaskets **58** and reducing the amount of milling work required on the backing blocks.

Casing **52** should provide adequate clearance between backing blocks **44** and the filter case **54** as well as the casing **52** itself so that substantially no energy will be lost or radiated in undesired directions from the sides or the rear of the assembly. In exceptional cases the casing **52** may be evacuated to prevent the transmission of compressional wave energy across it. As pointed out in my above-mentioned copending application, the reception of energy through the sides or rear of a directional receiving device is particularly undesirable in submarine detecting systems for use on naval craft since the propeller noise from the craft itself will then be very likely to mask the relatively weak sound waves from a distant submarine. Wiring between the crystals and filter, etc., is not shown in Figs. 2 and 3 as it would, it is felt, render the drawing obscure. Also relay switching devices **28** of Fig. 1A are not shown in Figs. 2 and 3 but the necessary arrangements including appropriate wiring, can, of course, readily be inserted in accordance with the diagram of Fig. 1A by one skilled in the art.



In addition to affording increased radiation the inclusion of nine crystal groups in each row broadens the radiation or response pattern of the device of Figs. 2 and 3 in the plane of the row. Since the device will normally employ its prismatic properties in the horizontal plane, the broadening just mentioned will occur in the vertical plane. For submarine detection work this is desirable as it will compensate for the roll of the vessel upon which the radiator or receiver is carried. Typical response or radiation patterns at several frequencies over a range of vertical and horizontal angles are shown in Figs. 4 and 5, respectively. In Fig. 4 the solid line curve **64** is the response at the lower edge of the filter pass-band, i. e., 18 kilocycles, while the dash curve **66** is the response at the upper edge of the pass-band, i. e., 24 kilocycles. In Fig. 5 curves **68**, **70** and **72** are for frequencies of 18.4, 20.6 and 23.6 kilocycles, respectively. The model thus formed is five wave-lengths long in the horizontal and three wave-lengths long in the vertical plane at the lowest operating frequency of 18 kilocycles.

For high power submarine radiators, the use of 45 degree Y-cut Rochelle salt piezoelectric crystals, or some cut of Rochelle salt crystal approximating the 45 degree Y-cut, offers substantial advantages as described in my above-mentioned copending application Serial No. 413,429. As mentioned above, the practicable maximum power output limit for crystal radiators is a point below that at which cavitation begins to take place. For a crystal submerged in an ordinary liquid, such as kerosene, for example, it has been discovered that cavitation will begin to occur at acoustic pressures of .85 to .90 atmosphere. When submerged in a highly viscous liquid, such as castor oil for example, it has been discovered that cavitation will not begin until an acoustic pressure in excess of five atmospheres has been reached. The adsorbed water of the crystal surfaces should, of course, be carefully removed and the castor oil or other highly viscous medium should be carefully dried as explained in my above-mentioned copending application Serial No. 413,429.

Since the power is proportional to the square of the acoustic pressure, the output power capacity of the crystal which can be realized without destruction of the crystal is increased in the order of twenty-five times by immersing it in a highly viscous liquid.

The greatly increased power which may be radiated with crystals immersed in a highly viscous liquid probably results from the sluggishness of the liquid, which flows so slowly that no cavities form during the short intervals in which negative pressure exists.

The increased power capacity of the individual crystal thus realized may be employed to advantage in constructing compressional wave radiators which will transmit in the order of twenty-five times the power of prior art radiators of like physical dimensions or it may be employed to obtain a given power radiation with a greatly reduced number of crystals and a much smaller over-all radiator structure than is required with prior art devices.

It is important that the cap enclosing the crys-

tals provide a sufficient volume and a cross-sectional area of the viscous fluid within it parallel to the radiating surfaces of the crystals. The cross-sectional area should expand substantially as the distance from the radiating surfaces is increased, so as to "spread" the power to an extent such that the acoustic pressure transmitted to the water in contact with the cap is somewhat less than an atmosphere. If effective spreading of the power is not realized, cavitation in the water with consequent loss of power will take place adjacent the outer surface of the cap and the efficiency of the radiator can be seriously impaired. This requirement of spreading the power is more readily satisfied for radiators of the type described in my copending application Serial No. 407,457, filed August 19, 1941, entitled "Radiating systems" in which, to reduce "minor-lobe" radiation (i. e., radiation at angles other than that of maximum radiation) the more central units of a multicrystal radiator are driven with greater power than the peripheral or end crystals. However, in any type of radiator the cap may readily be proportioned to afford an adequate spreading of the power and reduction of pressure to avoid cavitation at the cap's outer surface with the water or other medium into which it is to radiate energy. In the structure of Figs. 2 and 3 the spacings between crystal groups and between the rows of crystal groups provide in effect an immediate expansion of the cross-sectional area through which the energy is to be transmitted in the viscous fluid.

In radiators of the above type in which the successive groups of radiating elements are connected at corresponding points of successive sections of a wave filter, respectively, in order to obtain the particular desired distribution of the radiated power between the successive groups of radiating elements the impedance of the successive filter sections can be adjusted. For the purposes of this specification this process is designated as tapering the filter impedance and a filter so adjusted is designated as a tapered filter. For example, in the radiator illustrated in Figs. 1A, 1B, 2 and 3, if it is desired to drive each of the fourteen groups of crystals by substantially equal amounts of power, it is necessary to compensate for the attenuation in the filter structure and the absorption of power by the successive radiating groups as power is transmitted from the input terminals **32** toward the terminating resistance **26**. The diminution of energy is, of course, principally a function of the dissipation of the filter sections and the absorption of power by the successive crystal groups in the sequence. In a particular model it was found satisfactory to increase the impedance of each section by approximately five per-cent of the impedance of the preceding filter section to provide substantially equal power radiation from all fourteen rows of crystals. In this instance the impedance of the first section was 6000 ohms and the impedances of the successive sections were 6320 ohms, 6710 ohms, 7100 ohms, 7600 ohms, 8140 ohms, 8770 ohms, 9480 ohms, 10,320 ohms, 11,350 ohms, 12,600 ohms, 14,130 ohms, and 16,100 ohms, respectively.

Of course, if a distribution of power in which the more central units are to be driven with more power than the peripheral units is desired, for instance, to obtain smaller minor-lobe radiation, the impedance of the successive sections should increase more rapidly than above from the input end to the central unit and then either remain substantially the same or even decrease again to the end or terminating unit, depending upon the power distribution desired. The principles involved are, of course, those discussed in my above-mentioned copending application on Radiating systems, Serial No. 407,457, coupled with the well-known principle that the power which a load of a given impedance will absorb is a function of the impedance of the circuit from which the power is to be drawn.



For the illustrative model radiator mentioned above, a pass-band of 18 to 24 kilocycles was chosen as representative of a frequency range often employed in the art. The actual "cut-off" frequencies were 17685 cycles and 24033 cycles, respectively, so that the phase shift at 18 kilocycles was correct for a direction of $-90°$ and at 24 kilocycles it was for a direction of $+90°$. Each row of nine groups of four crystals each, was found to have substantially a static capacitance of 451 $\mu\mu f$, a motional capacitance of 29.8 $\mu\mu f$, an equivalent inductance of 1.922 henries, a distributed capacitance, mainly in the wiring, of 39 $\mu\mu f$ and a radiation resistance when the device was operating in sea water of 115,000 ohms. Fig. 1B shows, in electrical schematic form, the equivalent electrical circuit of a row of crystals as described above, condenser **38** representing the static and distributed capacitances, condenser **34** representing the motional capacitance, inductance **36** representing the equivalent inductance and resistance **40** representing the effective load into which the device is radiating. The impedance across the input terminals is substantially 115,000 ohms as stated above when radiating into sea water. The crystals are adjusted to be resonant at the mid-frequency of the range of frequencies to be used when the device is operating into the load impedance under which it is to be operated. In the model radiator the crystals were found to be resonant at the mid-frequency (21 kilocycles) of the range used with the device operating in sea water if they were designed for resonance at 24 kilocycles in air.

For a particular phase angle $\varphi$ between the radiation from successive rows of crystals (or other radiating units) the angular direction of radiation may be determined from the formula:

$$\sin\theta=\frac{\varphi}{\frac{\omega d}{v}} \qquad (1)$$

where $\omega$ is $2\pi$ times the frequency; $d$ is the separation between the center of successive radiating units (3 cm. for the illustrative model radiator of Figs. 1 to 3, inclusive); $v$ is the velocity of compressional-wave energy in the medium through which the radiation is to be effected; and $\theta$ is, of course, the angle at which radiation takes place. The angle-frequency relations for radiation in sea water ($v=1.5\times10^5$ cm. per second) are shown in the full-line curve **60** of Fig. 12. The probable extreme variations in directivity resulting from variation of the velocity of propagation with change in temperature are indicated by the dash-line curve **61** and the dash-dot line curve **62** for the lowest and highest probable temperatures of sea water, respectively. A minimum velocity of $1.45\times10^5$ cm. per second and a maximum velocity of $1.55\times10^5$ cm. per second appear reasonable limiting values for sea water.

For the radiation or reception of a band of frequencies with substantially uniform efficiency, it is desirable to correlate the mechanical and electrical components of the radiating or receiving system so as to comprise an electro-mechanical

band-pass wave filter passing the band of frequencies to be radiated or received.

For filters employing sharply resonant complex reactive elements such as piezoelectric crystals or magnetostrictive vibrators it has always been a problem to provide extremely wide pass-bands. This problem and a partial solution of it, including the use of an inductance in series with a crystal to permit broadening the pass-band of the filter are discussed in my Patent 1,921,035, issued August 8, 1933. However, a maximum band width in the order of 28 per cent of the mid-band frequency is the greatest that can be conveniently realized with substantially non-dissipative filter structures of the prior art employing Rochelle salt piezoelectric crystals or similar electromechanical resonant devices. Consequently, to cover a very wide range of frequencies with Rochelle salt piezoelectric crystal radiators or receivers, it is necessary to subdivide the wide range into a number of bands such that the width of each band, i. e., the difference between its lowest and highest frequencies, does not exceed approximately 28 per cent of its mid-frequency and then to construct a like number of crystal radiators designed as filters to pass the selected bands, respectively, the filters being arranged in accordance with well-known wave-filter design theory to be operated in parallel.

Such an arrangement is illustrated in Figs. 6 to 10, inclusive, where a wide range of frequencies (viz. 10 to 50 kilocycles, approximately) has been divided into five bands as indicated in Fig. 10 and a group of crystals designed for operation over the particular frequency band has been provided for each of the five bands as shown in Figs. 6 and 7. The group of crystals **80** comprises the radiator for the lowest band and the groups **82**, **84**, **86** and **88** are the radiators for the four successively higher bands, respectively. The crystal groups are each one-quarter wave-length of their respective mid-band frequencies in height and are provided with steel backing blocks **90**, **92**, **94**, **96**, **98**, respectively, each backing block also being one-quarter wave-length of the mid-band frequency of its associated group of crystals. As previously described, such an arrangement induces a node at the mounting plate and thus tends to eliminate the interaction of any vibrating crystal group upon the others and the loss of energy to the case.

The compartment containing the radiating groups should be filled with a liquid which has been thoroughly dried of water and which has an appropriate impedance. If high power is to be radiated, the liquid above-mentioned should, in addition to the other properties mentioned, be highly viscous to reduce difficulties from cavitation and a sufficient increase in radiating area between the crystal groups and the diaphragm **110** should obtain to reduce the acoustic pressure transmitted to the sea water on the outside of diaphragm **110** so as not to exceed one atmosphere. (It is assumed that the device is to be employed submerged in sea water.) A lining **103** of felt or other compressional-wave damping material is preferably provided to prevent energy from reaching case **89** and impairing the directive characteristics of the device. Auxiliary inductances **100**, **102**, **104**, etc., for use with the vibrating crystal groups may be mounted in the bottom of the case **89**. The wiring is not shown, to avoid confusing the drawing unnecessarily.



The action of each of the five units can be explained in connection with Figs. 8 and 9 as follows: The equivalent circuit in electrical schematic diagram form of any one of the five groups of crystals and its associated steel backing member is shown in Fig. 8.

In Fig. 8 capacity **114** is the combined static and distributed capacities of the radiator and its wiring, the transformer **116** represents the electromechanical impedance transformation involved in the coupling between the electrical and mechanical portions of the radiator, capacity **118** is the motional capacity (or mechanical compliance) of the crystal, and inductance **120** represents the equivalent inductance (mass) of the crystal. If the length and width of the radiating surface of a crystal group are each substantially one-half wave-length or greater the effective radiation resistance of the medium to the radiator (castor oil or the like) will be very closely equal to $\rho v$ the radiation resistance of water. If an electrical coil is now added in series with the crystal input the combination can be designed in accordance with classical filter design theory as an electromechanical band-pass wave filter having a pass-band which is as broad as 28.4 per cent of its mid-band frequency, provided 45° Y cut piezoelectric Rochelle salt crystals or similar crystals of the proper dimensions are employed. The following table gives, by way of illustration, design data for the group of five units of Figs. 6 and 7 and having pass-bands as indicated in Fig. 10:

| Pass-band in kc. | Crystal dimensions in cm. | | | No. of crystals | Inductance of added coil M. H. | Length of steel backing member, cm. |
|---|---|---|---|---|---|---|
| | Length | Width | Thickness | | | |
| 10 to 12.8 | 5.4 | 2.5 | 0.936 | 24 | 491 | 10.6 |
| 14 to 18 | 3.85 | 2.62 | .67 | 16 | 359 | 7.57 |
| 19.6 to 25.2 | 2.745 | 2.5 | .64 | 16 | 248.5 | 5.4 |
| 27.45 to 35.3 | 1.955 | 2.0 | .53 | 16 | 177.5 | 3.85 |
| 38.5 to 49.4 | 1.392 | 1.5 | .40 | 16 | 127.9 | 2.74 |

Fig. 9 represents the piezoelectric crystal group of Fig. 8 with a series inductance **122** as above described and a terminal load resistance **124** representing the impedance of the liquid load on the vibrating crystal group. The filter units thus formed will have an impedance slightly less than 9000 ohms, and when connected with their inputs electrically in parallel, the five units provide substantially uniform radiation or reception of compressional-wave energy over the extremely wide range of frequencies from 10 to 50 kilocycles, inclusive. Prismatic properties may of course be imparted to each group of vibrating crystals by the straight-forward application of the principles described in detail above in connection with Figs. 1A, 2 and 3 inclusive of the accompanying drawings.

The above arrangements are preferred illustrative embodiments of the principles of the invention. Numerous other arrangements within the

spirit and scope of the invention will readily occur to those skilled in the art. For example, while the above illustrative embodiments employ groups of piezoelectric vibrators it is obvious that magnetostrictive, electromagnetic or other vibrating members could be substituted therefor and the prismatic properties, the increased power radiation and the like improved performance characteristics, can be realized. The scope of the invention is defined in the following claims.

What is claimed is:

1. In a compressional-wave system a directive radiator and receiver of compressional-wave energy comprising the combination of a plurality of substantially identical piezoelectric crystal vibrators mounted with a corresponding vibrating surface of each vibrator aligned in a common plane and spaced less than one-half wave-length apart, a multisection electrical band-pass wave filter having a plurality of sections, the driving electrodes of successive crystal vibrators of said plurality of vibrators being electrically connected across a corresponding impedance branch of successive sections of said multisection electrical wave filter respectively whereby said crystal vibrators can be driven with any of a large number of phase relations between successive vibrators by selecting a frequency within the pass-band of said filter for which a section of the filter has the desired phase shift and the angular direction of effective radiation of compressional-wave energy by the array of crystal vibrators can thus be determined and controlled at will and whereby the effective angle of reception of compressional wave energy by the array of crystals is made dependent upon the frequency of the energy impinging upon the array, being different for each frequency within a particular predetermined band of frequencies.

2. In a compressional-wave energy system a plurality of electromechanical vibrating units in alignment, the center-to-center spacing between successive units being less than one-half wave-length of the highest frequency to be employed in the system, an electrical wave filter passing a band of frequencies within the useful frequency range of the system, said wave filter having a plurality of filter sections all transmitting the frequency region of interest and being substantially identical as to pass-band and phase characteristics and being equal in number at least to the number of vibrating units less one, the successive vibrating units being connected across a particular impedance arm of the successive filter sections, respectively, whereby when electrical energy having a frequency within the pass-band is transmitted longitudinally through said filter, successive vibrating units will be driven with a phase relation which is dependent upon the frequency selected and the direction of radiation of compressional-wave energy by said plurality of vibrating units will likewise be dependent upon the frequency selected or when compressional-wave energy of a particular frequency within the pass-band of the filter impinges upon said plurality of vibrating units and is converted by them into electrical energy the electrical energy to be withdrawn from said filter will be dependent upon the angular direction at which the compressional-wave energy approaches the vibrating units, the electrical energy for a particular frequency within the pass-band being maximum for a particular angle of approach and decreasing to substantially zero as the angle of approach becomes substantially different from the said particular angle.



3. The arrangement of claim 2 the successive sections of the wave filter being identical as to the band of frequencies transmitted by each and as to phase characteristics but of differing impedance whereby the power distribution to successive vibrating units is adjusted to produce a predetermined desired effect upon the directive characteristics of the assembly.

4. A prismatic compressional wave radiator and receiver comprising a plurality of electromechanical vibrating units aligned at intervals which are small with respect to the wave-length of the energy to be transmitted and received, said units being efficiently operative within a predetermined frequency region, a multisection electrical transmission device the sections thereof being substantially identical and freely passing said predetermined frequency region but imparting a different phase shift to each frequency thereof, the number of sections at least equalling the number of vibrating units less one, successive vibrating units being electrically connected at corresponding points of successive sections of said transmission device whereby each frequency within said predetermined region will be transmitted or received with greatest amplitude in a particular predetermined direction, the direction being different for each frequency.

5. The radiator and receiver of claim 4, the impedances of successive sections of the electrical transmission device differing progressively whereby a particular effective distribution of the total energy throughout the plurality of vibrating units is achieved and the directional properties of the assembly are modified in a predetermined desired manner.

6. In a multifrequency compressional wave transmission system the combination of a plurality of electromechanical vibratory units, a plurality of sections of an electrical transmission medium connected in series relation and freely transmitting all frequencies of said system but imparting a different phase to each frequency thereof the number of said sections being at least equal to the number of vibrating units less one and means for connecting successive vibrating units at corresponding points of successive sections of said transmission medium whereby the directive properties of said combination will differ for each frequency of the system.

WARREN P. MASON.