Aug. 6, 1946. W. P. MASON 2,405,225

SUBMARINE SIGNAL SYSTEM

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FIG. 1

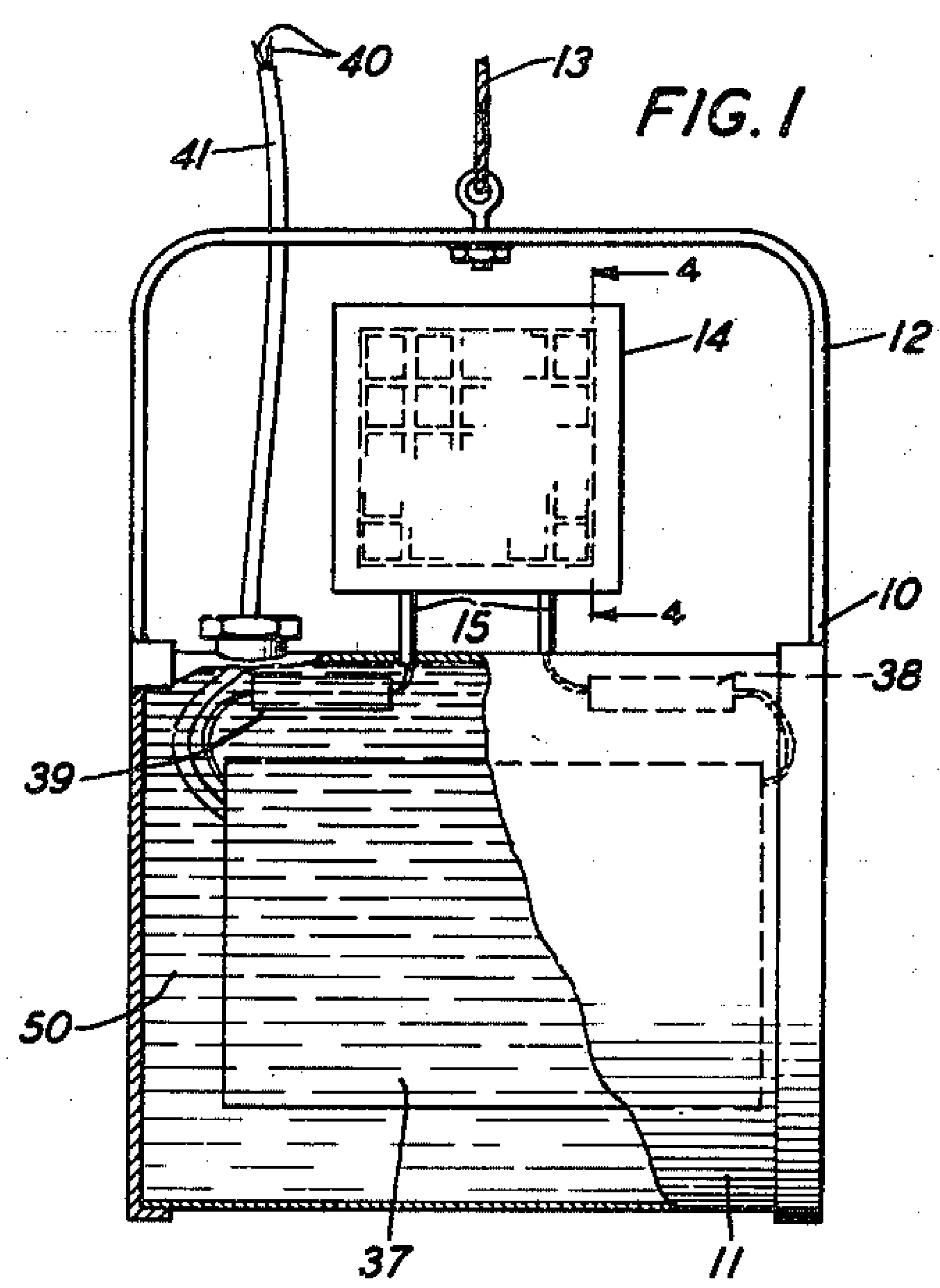

FIG. 2

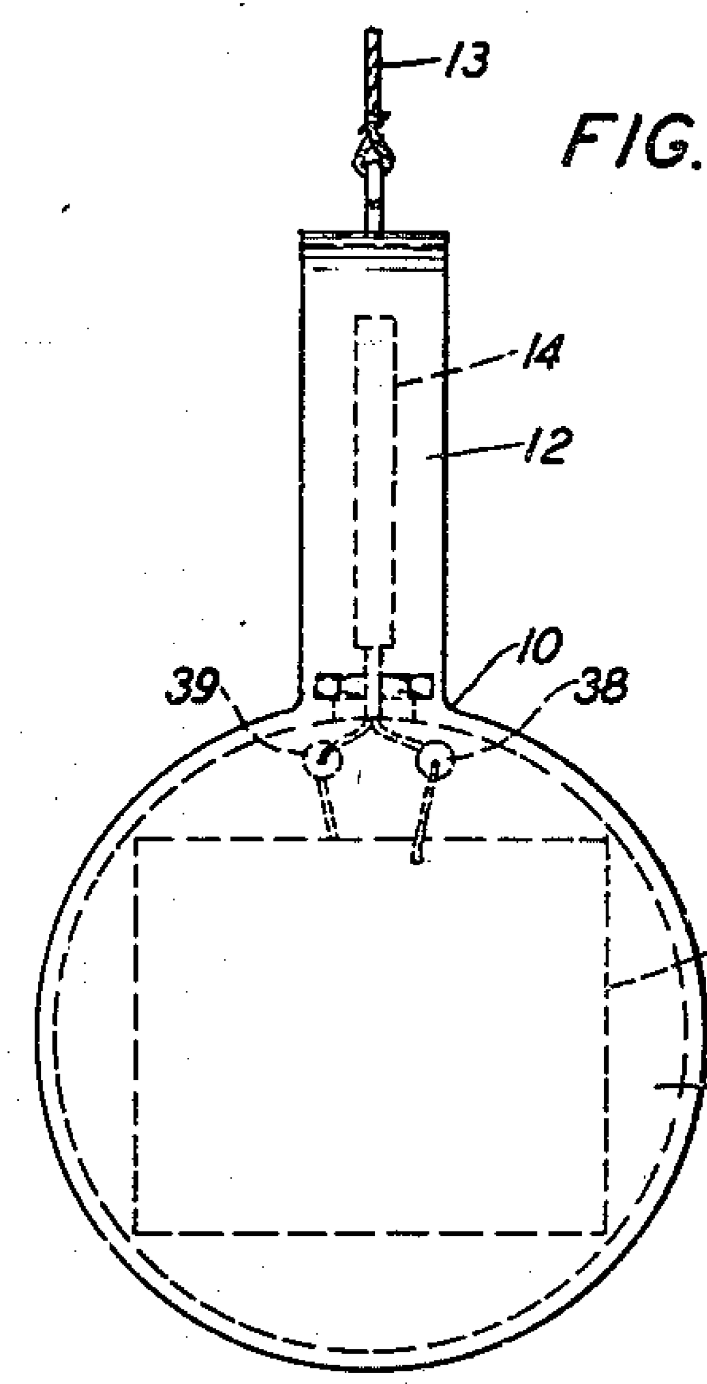

FIG. 3

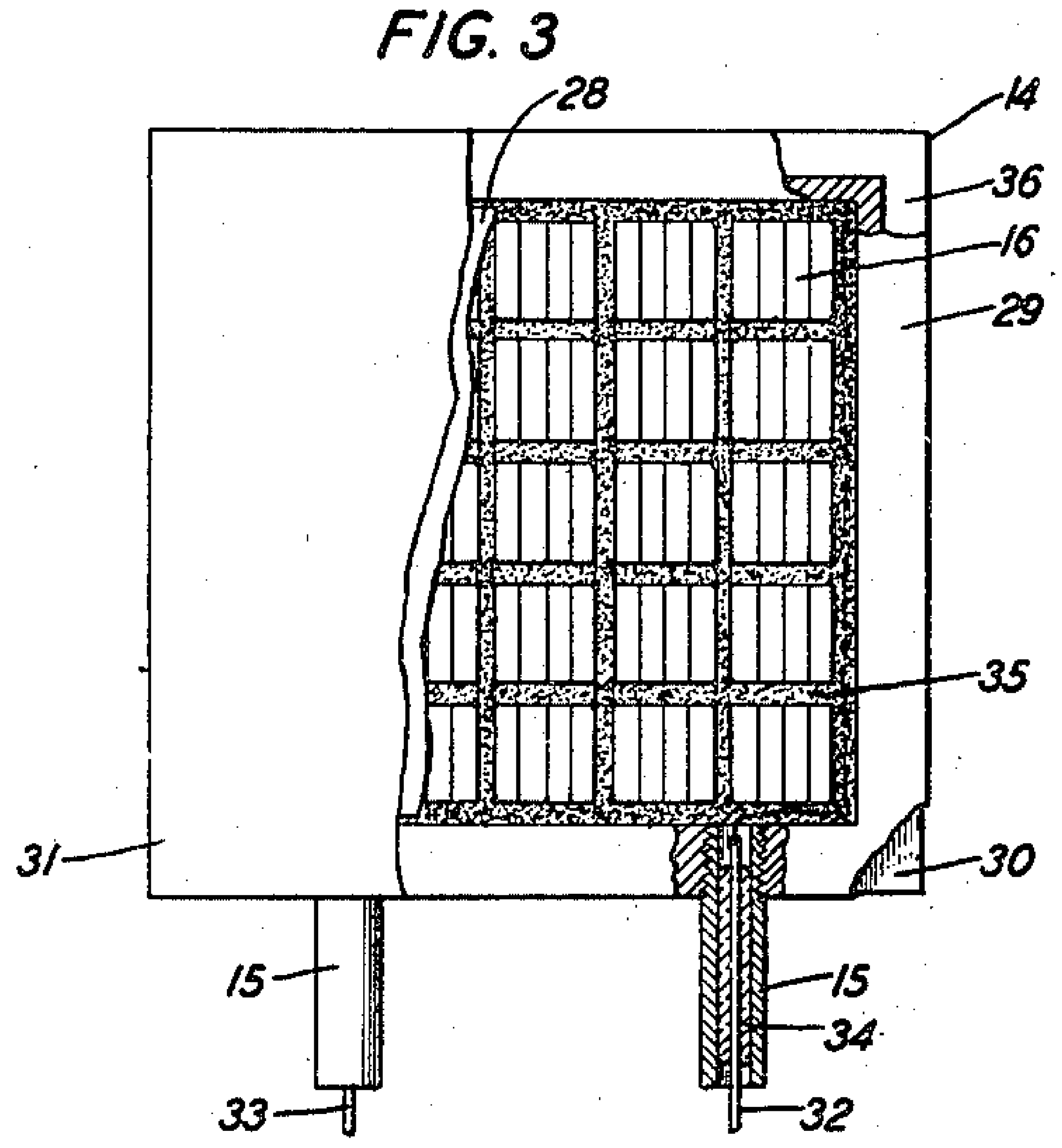

FIG. 4

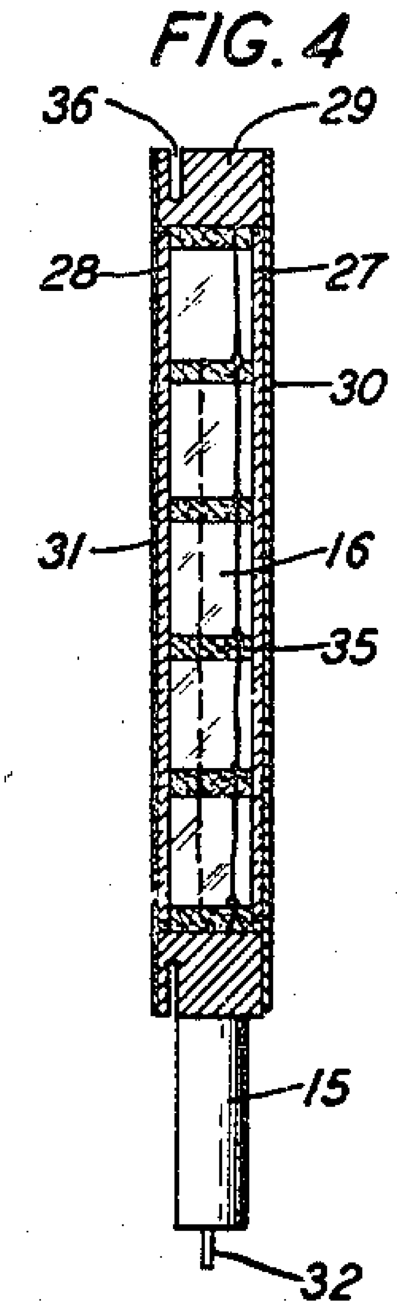

FIG. 3A

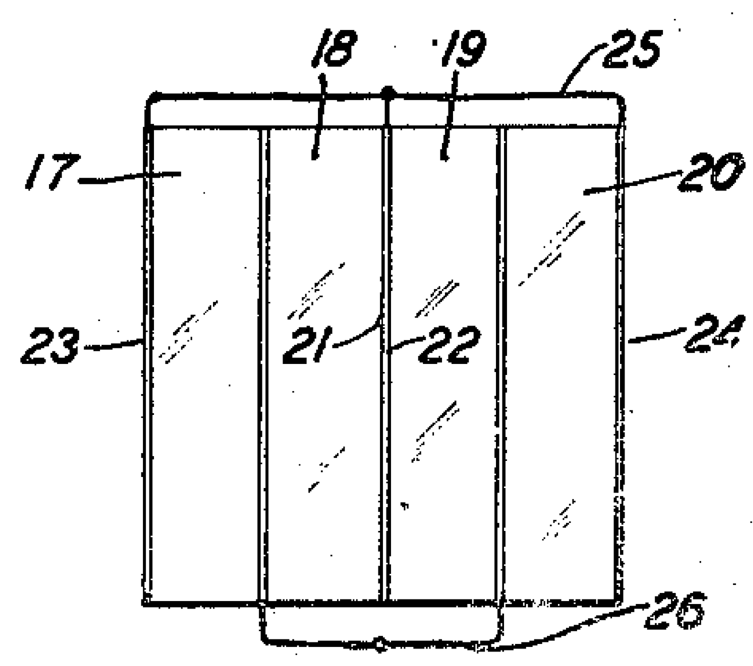

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FIG. 5

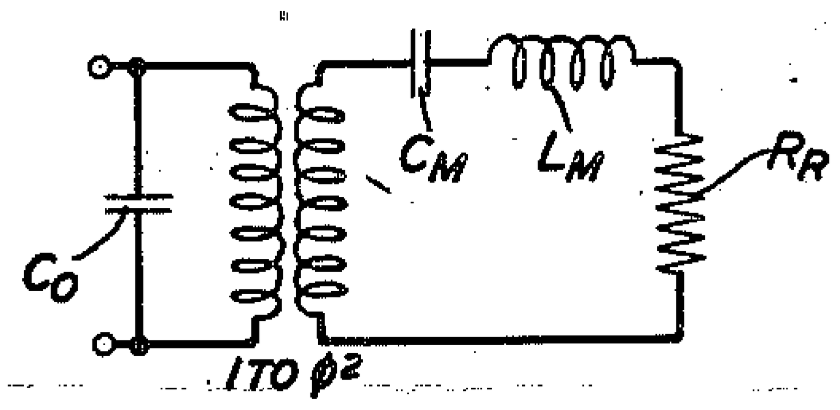


FIG. 6

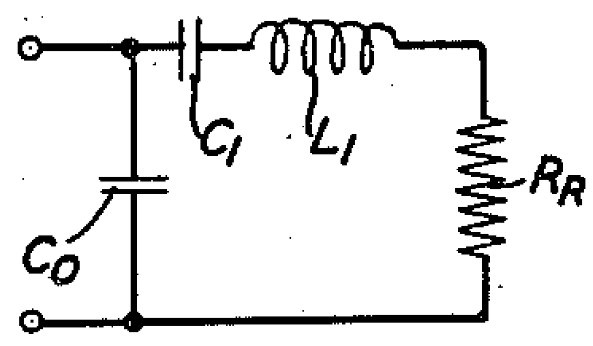


FIG. 7

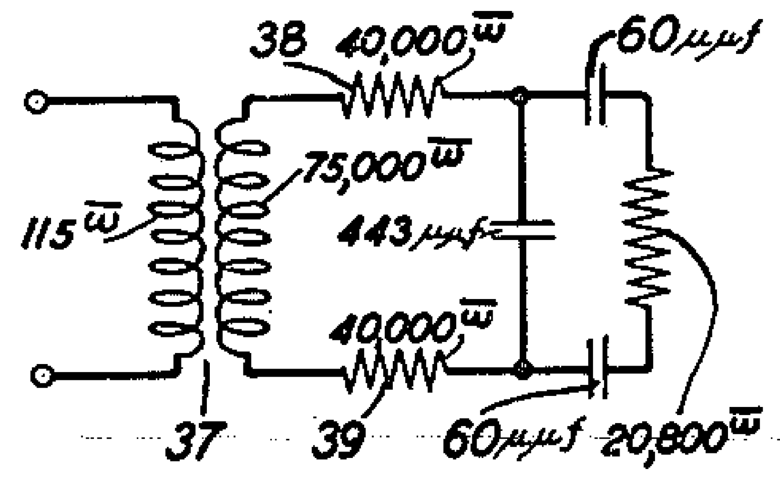
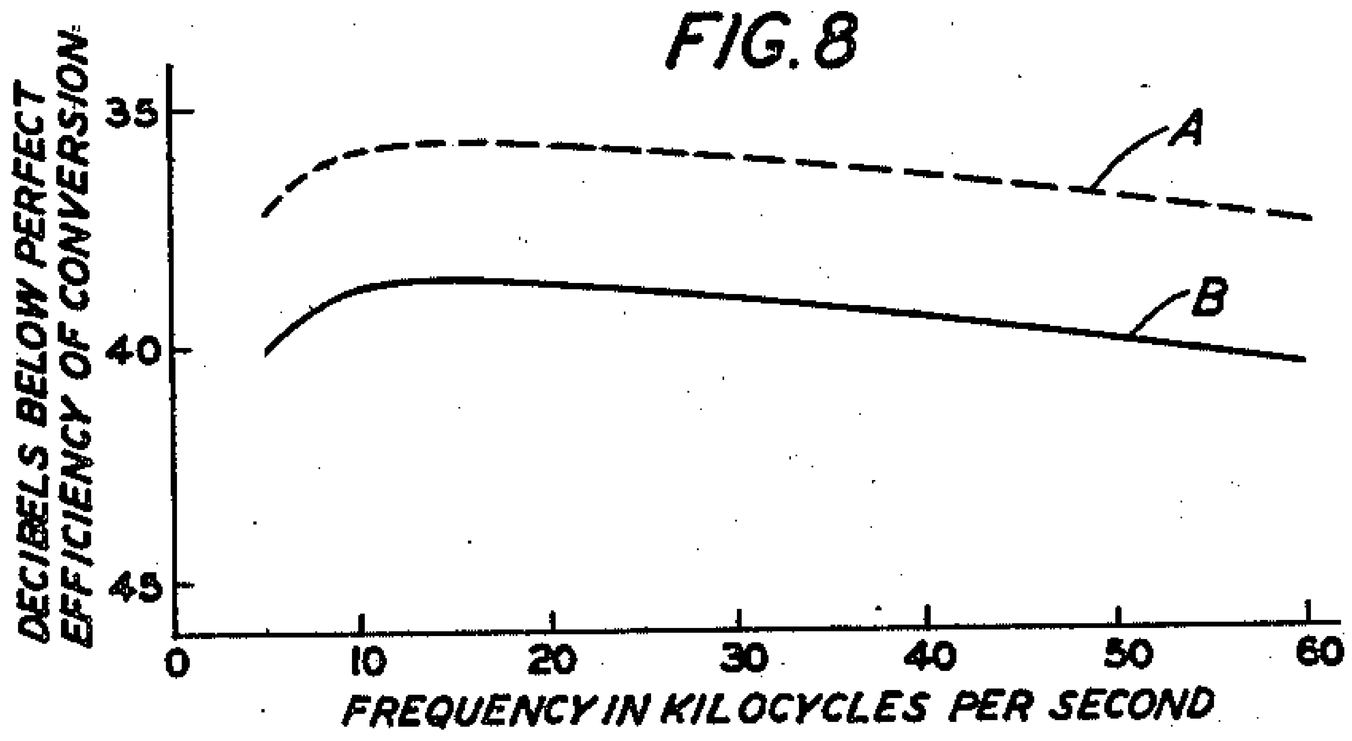


FIG. 8



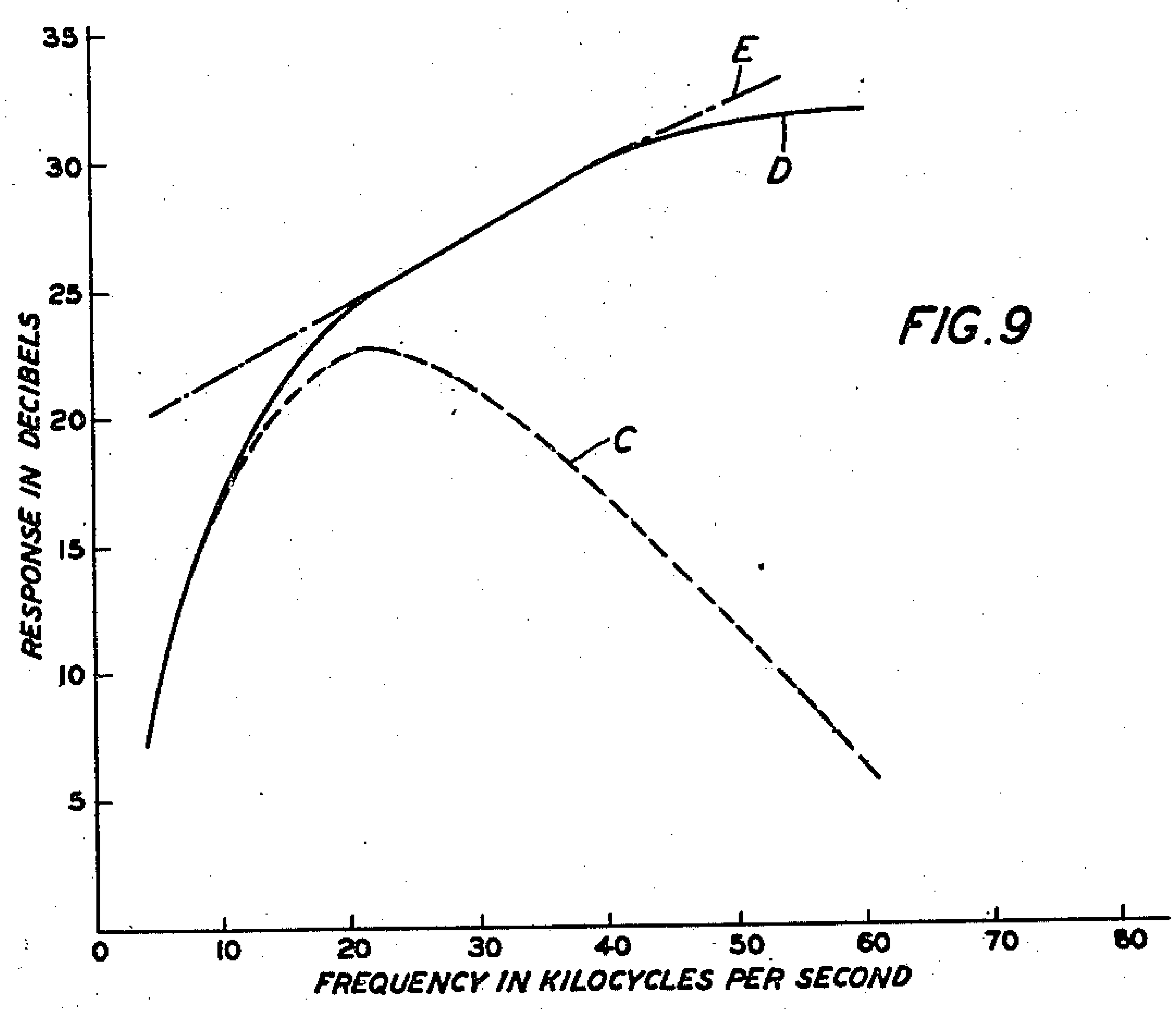


FIG. 9

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UNITED STATES PATENT OFFICE

2,405,225

SUBMARINE SIGNAL SYSTEM

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Application October 14, 1942, Serial No. 462,042

6 Claims. (Cl. 177—386)

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This invention relates to submarine signaling systems and more particularly to submarine signal projectors.

An object of this invention is to radiate or project signal waves of a wide range of frequencies into and under water.

Another object of the invention is to convert electrical signals into sonic or supersonic signals in water with substantially constant efficiency over a broad band of frequencies.

In accordance with the invention, the radiator or projector comprises piezoelectric crystal means, for example, electrically connected units or blocks of Rochelle salt crystals which may be of the 45-degree Y-cut type. The resonant frequency of the crystal means is preferably well beyond the upper limiting frequency of the frequency band of interest. Resistance means is connected in series with the crystal means and is chosen of such impedance as to be substantially equal to the reactive impedance of the crystal means at a relatively low frequency whereby, at the higher frequencies of interest, the current into the crystal means will be controlled by the resistance and be substantially independent of frequency.

A more complete understanding of the invention will be derived from the detailed description that follows, taken in conjunction with the appended drawings, wherein:

Fig. 1 shows a front elevational view of apparatus embodying the invention;

Fig. 2 shows a side elevational view of the apparatus of Fig. 1;

Fig. 3 shows a front view of the piezoelectric crystal means, projector or radiator included in the apparatus of Fig. 1, partly broken away and partly in section to show details of structure, and Fig. 3A an enlarged elevational view of one of the component crystal blocks of that means showing the electrical wiring connections between the individual crystal plates;

Fig. 4 shows a sectional view of the crystal means of Figs. 1 and 3 taken along the line **4—4** of Fig. 1;

Figs. 5, 6 and 7 show equivalent electrical circuits or analogues of the piezoelectric crystals in the projector of Figs. 1 and 3 under different conditions;

Fig. 8 shows curves illustrating the calculated efficiency of conversion with respect to frequency, of the arrangement of this invention; and

Fig. 9 shows curves evidencing the response-frequency characteristic determined from experimental tests of an actual embodiment of the invention.

Figs. 1 to 3, 3A and 4 illustrate a submarine

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signalling device or apparatus embodying the invention. It comprises a frame or support **10** having an enlarged, hollow, substantially cylindrical portion **11**, and a bail or carrier portion **12** whereby the device may be submerged or suspended at the end of rope or cable **13** in a body of water. A signal wave projector or radiator **14** is supported from the portion **11** by a pair of metallic tubes or pipes **15** through which electrical connections may be made between components in the hollow portion **11** and the projector.

The projector is constructed of a plurality of piezoelectric crystal units or blocks **16**. Each of these units may comprise four 45-degree Y-cut Rochelle salt crystals or plates **17**, **18**, **19**, **20**, each of which may be 1.6 centimeter long, 1.0 centimeter wide and .4 centimeter thick. When connected together they constitute a block or unit 1.6 cm. $\times$ 1.6 cm., with a width in the radiation direction of 1.0 centimeter. The crystal plates are coated on their faces with platinum-rhodium about .00017 inch in thickness. The innermost faces **21**, **22** and the two outermost faces **23**, **24** are connected together with a copper wire **25** to constitute one terminal of the unit; the intermediately located other two pairs of crystal faces are connected together by a second copper wire **26**. The crystal units, which, in a specific embodiment were twenty-five in number, are fastened to and between thin ceramic plates or discs **27**, **28**. The latter may be of the order of .1 centimeter thick. The crystal units-ceramic plates assembly is enclosed by a rectangular frame **29** the open ends of which are closed by a pair of phosphor-bronze diaphragms **30**, **31** of the order of .003 inch in thickness, soldered at their marginal portions to the frame **29** and fastened on their inner surfaces to the ceramic plates **27**, **28**.

The procedure in assembling the projector may be as follows. The crystal blocks **16** are connected in parallel by suitable wiring and arranged symmetrically, as shown, between the ceramic plates **27**, **28** to which they may be glued or cemented. The diaphragm **30** is soldered to the frame **29** and the crystal units-ceramic plates assembly fastened thereto by cementing the ceramic plate **27** to the inner surface of diaphragm **30**. By having the frame **29** of sufficient size, a small clearance may be provided between the crystal units for their wiring which terminates at the two leads **32**, **33**, brought out of the frame through the glass seals **34** in the tubes **15**; and for dry Rochelle salt **35** to keep the humidity low. The second diaphragm **31** is cemented to the ceramic plate **28**, and, after the assembly is thoroughly dried out, the diaphragm **31** is soldered to the frame **29**. To facilitate the latter soldering operation, a narrow slot **36** may be milled into the frame **29**. This carries little heat to the main frame and affords protection against overheating of the crystal units. As a further precaution against excessive heating of the crystal units, the assembly may be placed in a pan of water during the final soldering operation. The cement used is preferably one that has a very rubbery consistency when dry, and may be of the type known commercially as Vulcalock.

The portion **11** encloses a transformer **37** and a pair of electrical resistances **38**, **39**, the latter being connected in series with the parallel-connected crystal units and the secondary winding of the transformer, the portion **11** otherwise being oil-filled as shown by the dashed horizontal lines designated **50**. The primary winding of the transformer **37** is connected through the conductors **40** of the cable **41** with a source (not shown) of electric waves to be converted by the projector into signal waves in the water. This electric wave source may be in a suitable vessel on the surface of the water, or at a shore station. The projector is intended to radiate signal waves over a broad band of frequencies, for example, from about 10 kilocycles per second up to about 60 kilocycles per second, with substantially constant efficiency. The resonant frequency of the crystal means should be substantially higher than the upper limiting frequency of the band of interest. The resistances **38**, **39** are chosen so as to present a resistive impedance substantially equal to the reactive impedance of the crystal units at a very low frequency in the frequency band of interest, whereby at the higher frequencies of interest the current into the radiator will be controlled by the resistance and will be independent of the frequency. A further understanding of this aspect of the invention will be derived from the following discussion.

The equivalent electrical circuit or analogue of all of the crystals in parallel is shown in Fig. 5, which can be derived from the equivalent circuit of the crystal given in the inventor's paper, "Dynamic measurement of the elastic, electric and piezoelectric constants of Rochelle salt," Physical Review, volume 55, (1939), pages 775 to 789. The element values for a single crystal of the 45-degree Y-cut type, radiating on both sides, expressed in c. g. s. electrostatic units, become

$$C_0=\frac{l_w l_y K}{4\pi l_t}$$

$$C_M=\frac{8}{\pi^2}\left[\frac{l_y S_{22'}}{l_w l_t(1-k^2)}\right]$$

$$L_M=\frac{\rho l_w l_y l_t}{8}$$

$$\Phi=\frac{f_{25} l_w K}{8\pi C_{55} S_{22'}}$$

where

$K=10.0$=dielectric constant of 45-degree Y-cut Rochelle salt.

$S_{22'}=9.26\times10^{-12}$=inverse of Young's modulus along the length.

$\rho=1.775$=density of Rochelle salt.

$f_{25}=6.33\times10^{4}$=piezoelectric constant of Rochelle salt.

$C_{55}=3.04\times10^{10}$=shear elastic constant.

l_y=length of crystal along direction of vibration in centimeters.

l_w=width of crystal in centimeters.

l_t=thickness of crystal in centimeters.

With these values, the element constants become

$$C_0=\frac{.797 l_w l_y}{l_t}\text{ e. s. u.}$$

$$=\frac{.884\times10^{-12} l_w l_y}{l_t}\text{ farads}$$

$$C_M=\frac{8.16\times10^{-12} l_y}{l_w l_t}\text{ farads}$$

$$L_M=.222 l_w l_y l_t$$

$$\Phi=8.96\times10^{4} l_w\text{ e. s. u.}$$

$$=.0896 l_w\text{ in practical units.}$$

The transformer Φ transforms from mechanical impedance units (expressed as a ratio of force in dynes to velocity in centimeters per second) to electrical impedance units.

When the crystal is used to drive water and the radiating surface is a half wave-length or greater, the mechanical end of the equivalent circuit will be terminated by the radiation resistance

$$\frac{R_R}{2}$$

where

$$R_R=1.5\times10^5\, l_w l_t\text{ mechanical ohms}$$

In general, the electrical impedance as measured from the electrical terminals of the crystal is of interest. For such a case, the mechanical elements can be taken through the electromechanical transformer, the resulting elements as shown in Fig. 6 being

$$C_0=\frac{.884\times10^{-12} l_w l_y}{l_t}\text{ farads}$$

$$C_1=\frac{7.25\times10^{-14} l_w l_y}{l_t}\text{ farads}$$

$$L_1=\frac{25.0 l_y l_t}{l_w}\text{ henries}$$

$$R=\frac{8.41\times10^{6} l_t}{l_w}\text{ ohms}$$

In the specific embodiment constructed in accordance with the invention, one hundred crystals were included. With dimensions $l_y=1.0$ centimeter, $l_w=1.6$ centimeters, and $l_t=.4$ centimeter, the constants for twenty-five parallel connected blocks of four crystals each become

$$C_0=437.0\ \mu\mu\text{f}$$
$$C_1=29.4\ \mu\mu\text{f}$$
$$L_1=.0625\text{ henries}$$
$$R=21{,}000\text{ ohms}$$

The distributed capacity resulting from the presence of the diaphragms **30**, **31** is kept low by the inclusion of the ceramic plates **27**, **28** between the crystals and diaphragms. In the particular structure, the added capacitance was about 450 $\mu\mu$f.

The resonant frequency for this crystal combination is over 100 kilocycles per second. Hence, up to about 50 kilocycles per second, the mass reactance may be neglected and the equivalent circuit may be represented by Fig. 7. The resistances **38**, **39** are included in series with the crystal means, and with the secondary winding of the transformer **37**. If the resistances are chosen to have a resistive impedance equal to the reactive impedance of the crystal at a relatively low frequency, at the higher frequencies of interest the current into the radiator will be controlled by the resistance and will be independent of the frequency. The impedance presented by the radiator will be primarily the capacitive reactance of the shunt condenser and, hence, substantially all of the input current flows through such condenser, whereby the voltage thereacross is inversely proportional to the frequency. The current into the radiation resistance is controlled primarily by the series capacitance since this presents a much larger impedance than the resistive impedance. Consequently, the current into the radiation resistance will be independent of frequency.

In using the described device to produce a definite pressure, account should be taken of the fact that the radiating surface becomes more directive the higher the frequency because the radiator becomes a larger number of wave-lengths at the higher frequencies. It can be shown that the increased directivity results in an increase in pressure equal to 6 decibels per octave for all frequencies of interest.

With the equivalent circuit of Fig. 7, the efficiency of conversion from electrical to mechanical energy can be readily calculated. The series resistance (R_A) added by the resistances **38**, **39** was taken as 80,000 ohms. In the particular case, the transformer **37** transformed from 115 ohms to 75,000 ohms but its loss was less than .5 decibel from 5 to 100 kilocycles per second. From a 75,000-ohm source (R_S) the current i_0 into the radiation impedance is given by

$$i_0=\frac{E}{\frac{-j}{\omega C_1}+(R_A+R_S)\left(1+\frac{C_0}{C_1}\right)+R_R+j\omega(R_A+R_S)R_RC_0}$$

The current into the radiation resistance (R_R) if connected to the sending resistance R_S by a perfect transformer would be,

$$i_0'=\frac{E}{2\sqrt{R_SR_R}}$$

Hence the efficiency of conversion is given by the ratio,

$$\frac{i_0}{i_0'}=\frac{2\sqrt{R_SR_R}}{\sqrt{\left[(R_A+R_S)\left(1+\frac{C_0}{C_1}\right)+R_R\right]^2+\left[\omega(R_A+R_S)R_RC_0-\frac{1}{\omega C_1}\right]^2}}$$

With the values R_A=80,000 ohms, R_S=75,000 ohms, R_R=21,000 ohms, $C_0=942\times10^{-12}$ farads, $C_1=29.7\times10^{-12}$ farads, the calculated efficiency of conversion is shown by the dotted curve A of Fig. 8. This represents the efficiency of conversion from electrical to total acoustic energy. When using the device to measure pressure, only the energy on one side is useful so that for radiation from one side the conversion efficiency is three decibels lower as shown by the solid curve B of Fig. 8.

Fig. 9 shows an experimentally obtained response-frequency characteristic of the device described hereinabove. The input to the projector was ten watts, the pick-up microphone being located two feet distant in the water from the projector and the microphone amplifier having a gain of 80 decibels. The dotted curve C represents the composite response of the projector, microphone and recording system associated therewith. After correction for the system and the microphone response as a function of frequency, the solid curve D was obtained as the projector response-frequency characteristic. The dot-dash line E represents a characteristic in which the response varies by six decibels per octave. The divergence of curves D and E is a measure of the variation in the conversion efficiency of the projector with frequency. It will be observed that between 10 and 60 kilocycles per second, the variation is of the order of only two decibels.

Although this invention has been disclosed with reference to a specific embodiment, it will be understood that it is not limited thereto but is of a scope evidenced by the appended claims.

What is claimed is:

1. A submarine signal projector for signal radiation over a broad band of frequencies with substantially constant conversion efficiency, comprising a plurality of 45-degree Y-cut Rochelle salt crystals connected in parallel, and electrical resistance means connected in series with said crystals and having a resistive impedance substantially equal to the reactive impedance of the crystals at a relatively low frequency in the band.

2. Submarine signaling means comprising a plurality of 45-degree Y-cut Rochelle salt crystals connected in parallel, and electrical resistance means connected in series with said crystals and of a resistive impedance substantially equal to the reactive impedance of the crystals at a relatively low frequency in the band of frequencies below the resonant frequency of the crystals.

3. Submarine signaling means comprising a plurality of 45-degree Y-cut crystals for translating electric energy into signal waves in water over a band of frequencies the upper limiting frequency of which is substantially lower than the resonant frequency of the crystals, and electrical resistance means in series with said crystals and of a resistive impedance substantially equal to the reactive impedance of the crystals at a relatively low frequency in said band.

4. A device for converting electrical energy into acoustic energy for radiation to a water medium with substantially constant efficiency over a wide band of frequencies, comprising a housing adapted for submersion in the water medium, including a frame and a pair of diaphragms affixed to and extending across the open portions of said frame so as to provide an enclosed space therebetween, a pair of thin electrically insulating plates each respectively affixed to and contacting substantially the entire inner surface of a different one of said diaphragms, a plurality of piezoelectric crystal units connected electrically in parallel with each other and supplied with electrical energy of said band of frequencies, each of said units comprising a plurality of electrically-connected Rochelle salt crystals, said plurality of crystal units being fastened to and arranged between said insulating plates within said space so that the array thereof, collectively, contacts substantially the entire inner surfaces of the insulating plates, thereby applying the mechanical vibrations produced in them in response to the supplied electrical energy through said insulating plates uniformly over the entire area of each of said diaphragms, the outer surfaces of both of said diaphragms contacting directly with and radiating acoustic energy to said medium when said housing is submerged therein.

5. The device of claim 4, in which each Rochelle salt crystal in each of said crystal units is 45-degree Y cut and said crystal units are separated from each other and said frame by dry Rochelle salt crystals to maintain the humidity low within said enclosed space.

6. The device of claim 4 in which each Rochelle salt crystal in each crystal unit is 45-degree Y cut, said crystal units being assembled symmetrically within said enclosed space in a plurality of rows each comprising the same number of units, extending between different portions of the two insulating plates, the assembly being one crystal wide in the radiation direction, so that all the individual crystals vibrate in unison in response to the supplied electrical energy to provide uniform vibration of all parts of each diaphragm through the insulating plates.

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