

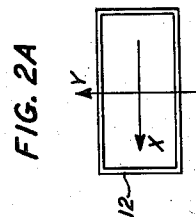
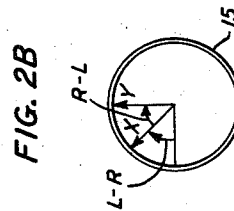
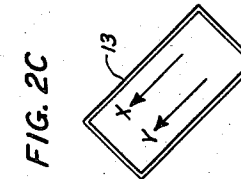
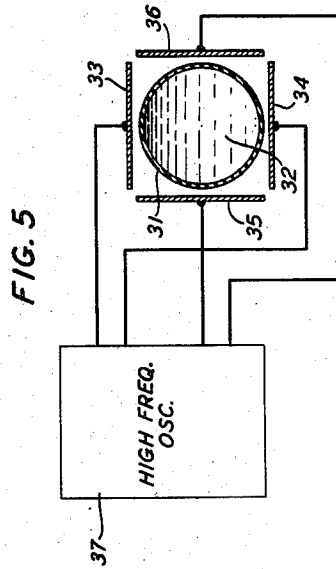
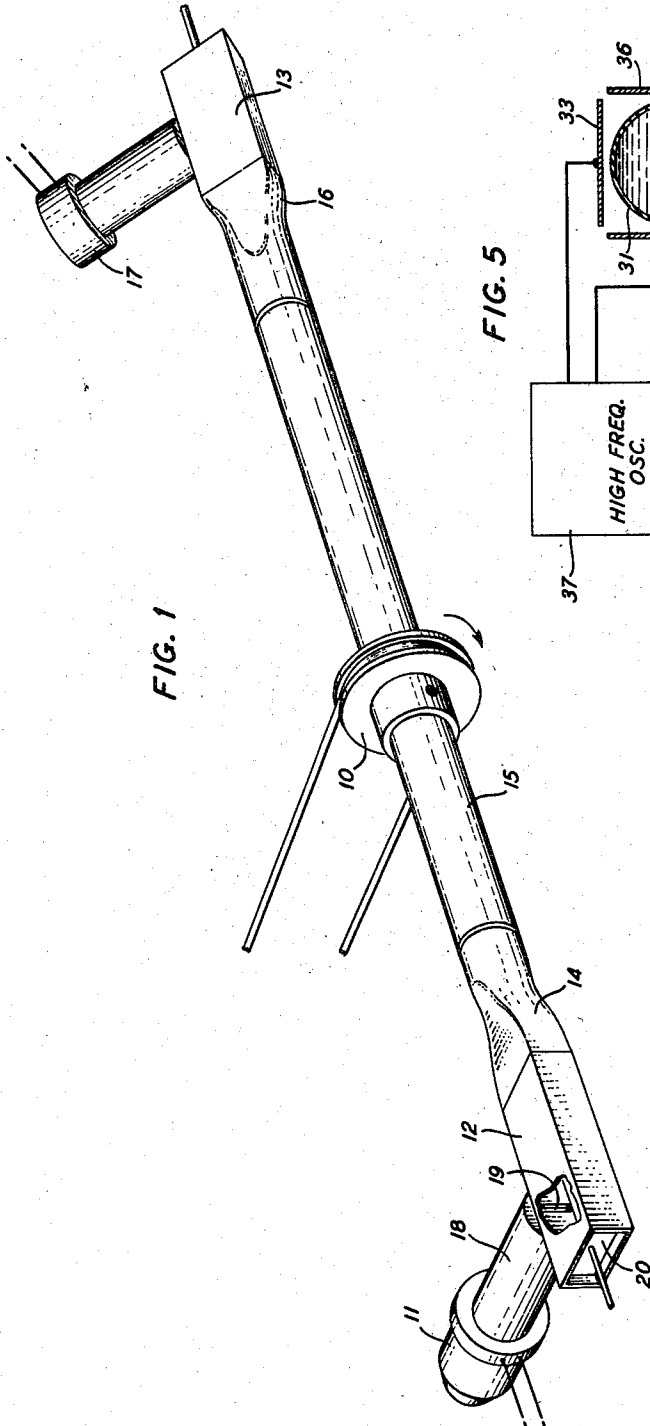
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W. E. KOCK
ACOUSTIC TRANSMISSION SYSTEMS

2,872,994

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2 Sheets-Sheet 1



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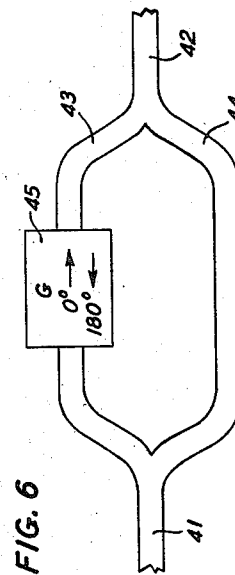
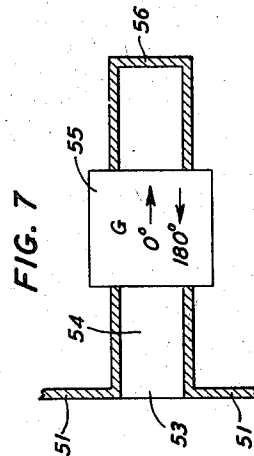
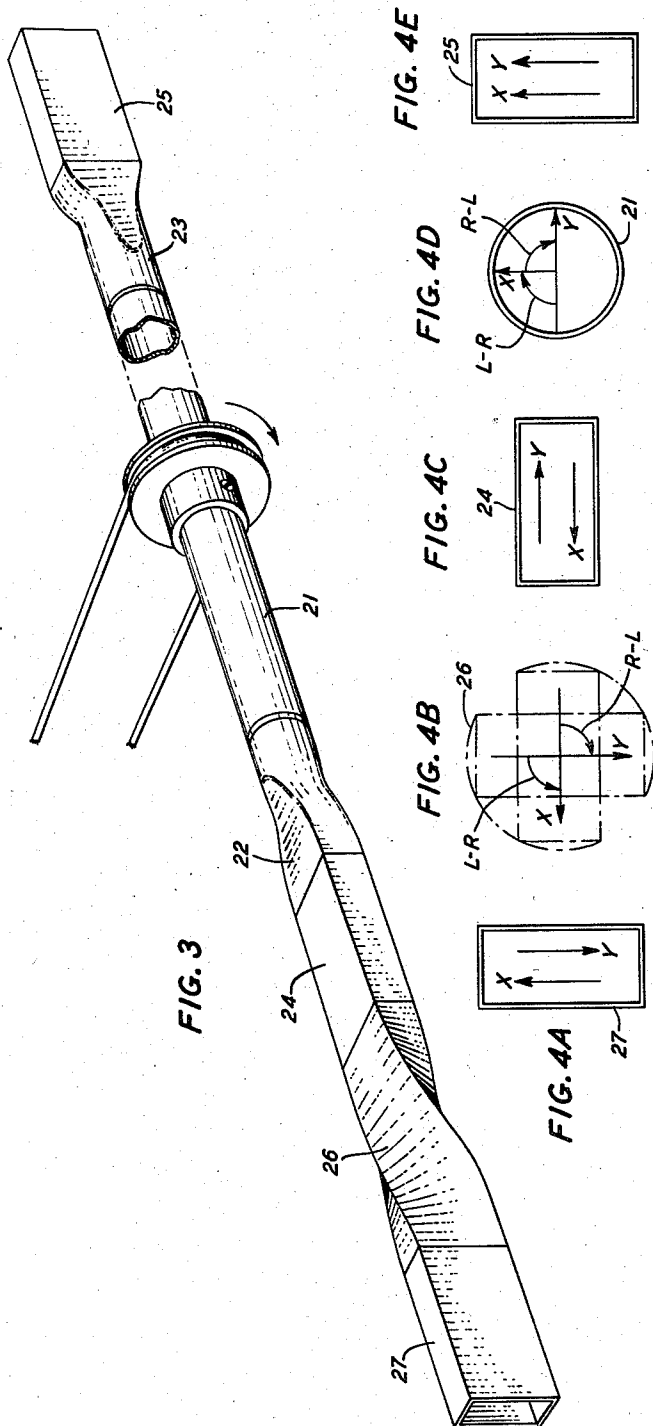
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ACOUSTIC TRANSMISSION SYSTEMS

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2 Sheets-Sheet 2



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ACOUSTIC TRANSMISSION SYSTEMS

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22 Claims. (Cl. 181—5)

This invention relates to acoustic transmission systems.

An electrical element which has the property of 180 degrees difference in phase shift between the two directions of propagation has been termed a "gyrator." Certain specific electrical transducers of this type are suggested in McMillan's articles in the Journal of the Acoustical Society of America, volume 18, pages 344 through 347; volume 19, page 922. In an article by C. L. Hogan, appearing on pages 1 through 31 of the January 1952, issue of the Bell System Technical Journal, an electrical "gyrator" for microwave frequencies is discussed.

One object of the present invention is to provide an acoustic "gyrator," or a sound transmission channel in which there is a difference in phase shift of 180 degrees between the two directions of transmission.

Another object of the present invention is to provide an acoustic system having different acoustic transmission properties for one direction of transmission than for the opposite direction of transmission.

Still another object of the invention is to effect the interconversion of longitudinal acoustic waves and transverse acoustic waves.

In accordance with one aspect of the invention, two sound transmission channels are coupled by a link which provides 180 degrees difference in phase shift between the two directions of transmission. From another viewpoint, the invention resides in the provision of a transmission link in which the sound transmission medium is disturbed asymmetrically with respect to the two directions of transmission. More particularly and in accordance with a specific embodiment of the invention, the plane of polarization of polarized acoustic waves passing through a sound transmission medium may be rotated by the bodily rotation of the medium, thus producing non-reciprocal transmission.

One feature of the invention resides in its applicability to the construction of various one-way sound systems.

Another feature of the invention resides in a simple longitudinal-and-transverse acoustic mode interconversion structure including an elongated acoustic channel having a transverse aperture which has a longitudinal dimension which is small with respect to the operating wavelength.

Other objects, features and advantages of the present invention will be apparent from the detailed description of certain specific embodiments illustrating the principles of the invention, which appear in the drawings.

Fig. 1 illustrates a one-way sound transmission system having axially aligned input and output sound transmission channels oriented at 45 degrees to one another with respect to their common axis;

Figs. 2A to 2C represent diagrammatically the operation of the device of Fig. 1;

Fig. 3 shows another type of non-reciprocal acoustic system;

Figs. 4A to 4E represent diagrammatically the operation of the device of Fig. 3;

Fig. 5 shows a device for shifting the plane of polarization of acoustic waves which may be substituted for the comparable element of either Figs. 1 or 2;

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Fig. 6 is a schematic representation of another one-way acoustic transmission system; and

Fig. 7 illustrates an application of the acoustic gyrator.

The devices of Figs. 1 and 3 employ polarized acoustic waves which have their plane of polarization rotated in passing through a rotating sound transmission medium. In contradistinction to the expected reciprocal polarization rotation, however, the rotating sound transmission medium rotates the plane of polarization of incident acoustic waves in the same direction irrespective of the direction of transmission of the sound waves. The structures which will be described in greater detail hereinafter employ this principle to obtain one-way transmission and other non-reciprocal acoustic properties.

Referring in detail to the drawings, Fig. 1 shows, by way of example, a sound source 11 energizing a rectangular acoustic channel 12 in its lowest order transverse mode of excitation in a manner which will be described in greater detail hereinafter. This channel 12, as well as the corresponding channel 13 at the other end of the acoustic system, are polarization discriminative, and can only support transverse oscillations polarized parallel to the wider sides, at the frequency of the sound source. This transverse acoustic wave propagates down the channel 12, through a rectangular-to-round channel transition section 14 and into a tube 15 which is rotated clockwise at a predetermined speed by the belt driven pulley 10. The air within the tube is also rotating, and rotates the plane of polarization of the polarized acoustic waves as they travel the length of the tube. From the tube 15, the acoustic waves pass through a second transition section 16 into the polarization-selective rectangular channel 13 which is axially aligned with channel 12 but displaced clockwise about their common axis by an angle of 45 degrees. The microphone 17 is coupled to this channel 13 through a mode-conversion structure which will be discussed in greater detail hereinafter, and is responsive to transverse waves in this channel.

The one-way operation of the device will be explained in connection with the diagrams of Figs. 2A, 2B and 2C. Considering first transmission from left to right, a transverse acoustic wave polarized to be parallel to the wider side of channel 12, as indicated by the vector "X," is shifted in plane of polarization by 45 degrees as it passes through tube 15 so that it is aligned with the wider side of channel 13 and is thus accepted by this channel. If acoustic waves polarized to the wider parallel side of channel 13 are transmitted from right to left, however, as shown by vector "Y" in Figs. 2C, 2B and 2A, taken in that order, they are rotated 45 degrees in the same sense by tube 15, as viewed from channel 12, and emerge from the tube perpendicular to the wider side of channel 12. The polarization discriminative channels cannot support transverse acoustic oscillations perpendicular to their longer sides, and thus these waves are not accepted by channel 12. It may thus be seen that the device of Fig. 1 transmits transverse acoustic waves of a given frequency from left to right but not from right to left.

The amount of rotation of plane of polarization for a given speed of rotation of a rotating tube may be approximately determined from the following formula:

$$\theta = 360 \times \frac{ln}{c}$$

where θ is the rotation in degrees, l is the length of the rotating tube in feet corrected for end effects, c is the velocity of sound, and n is the angular velocity of the rotating tube in revolutions per second. It may be noted that n is also equal to the angular velocity of the plane

of polarization in revolutions per second when the sound transmission medium has the same angular velocity as the tube. This may be assured by the use of thin sound transmitting diaphragms secured to each end of the tube 15. When the diaphragms are omitted, the angular velocity of sound transmission medium is slightly less than that of the tube. With the frequency and channel dimensions noted hereinafter, the amount of rotation of the plane of polarization is approximately 45 degrees with a 2.3 foot length of pipe rotating at 3600 revolutions per minute assuming c equal to 1100 feet/second, and assuming that the sound transmission medium rotates with the same angular velocity as the tube 15. Because of such variables as the speed of sound and the end effects with different interior channel surfaces, a variable speed drive is employed for the rotation of the tube 15 to secure the desired angular plane of polarization rotation.

The conversion of the longitudinal acoustic waves generated by the sound source 11 into transverse waves in the channel 12 is effected by the relative orientation of the acoustic channels 18 and 12, the location and size of the coupling aperture 19, and the use of the adjustable piston 20. More specifically, the circular acoustic tube 18 is oriented at right angles to the axis of the rectangular channels 12 and 13, and is parallel to the wider sides of the channel 12. One end of the tube 18 is coupled to the speaker 11, and the other end is closed with the exception of the aperture 19 which is common to the closure at the end of tube 18 and to one of the narrower side walls of the channel 12. Because the lowest order transverse acoustic mode characteristically has a uniformly higher pressure along one narrow wall of the channel, a neutral pressure plane between the center lines of the two wider walls of the rectangular channel, and a rarefaction or low pressure area along the other narrow wall, an aperture in one of the narrower side walls of the rectangular guide is best suited for the excitation of this mode. Furthermore, because of the change from rarefaction to compression at half wavelength intervals along the length of the channel at a given instant, the aperture should be relatively small with respect to a wavelength, and should not exceed a half wavelength in longitudinal extent. The distance of the piston 20 from the aperture 19 is adjusted to provide a maximum ratio of wanted to unwanted modes, taking advantage of the difference in wavelength of these modes. Maximum reinforcement of the desired mode is to be expected at an integral number of half wavelengths from the aperture. Minimum reinforcement for the other mode is to be expected at an odd number of quarter wavelengths for this mode. By adjusting the piston over several half wavelengths, a position yielding the desired high ratio of wanted to unwanted mode can be determined. In the case at hand, the wavelength of the undesired longitudinal mode is the same as that of sound in free space, and that of the lowest order transverse mode is

$$\lambda_t = \frac{\lambda_0}{\sqrt{1 - \left(\frac{\lambda_0}{2a}\right)^2}}$$

where λ_t is the wavelength of the transverse mode, λ_0 is the wavelength of sound in a continuous medium of the type found in the rectangular channel, and a is the larger internal cross-sectional dimension of the rectangular acoustic channel. The arrangement of side excitation and piston adjustment thus serves to transform the longitudinal acoustic oscillations in the tube 18 into the lowest order transverse vibrational mode in the channel 12. An identical mode transformation structure is provided at the other end of the transmission system to reconvert from the transverse to the longitudinal mode.

Using a 9,000 cycle per second sound source, for example, the rectangular channel could have cross-sectional dimensions such as $1\frac{1}{4} \times \frac{5}{8}$ inches. With the half wavelength or cut-off dimension for the lowest order trans-

verse mode at 9,000 cycles per second equal to approximately $\frac{3}{4}$ inch, it is clear that the rectangular acoustic channel can support transverse oscillations parallel to the $1\frac{1}{4}$ inch side but not parallel to the $\frac{5}{8}$ inch side. From the foregoing technical data, suitable operating conditions may be established to obtain one-way transmission of the type shown in the system of Fig. 1, within the limitations of available apparatus.

The "acoustic gyrator" of Fig. 3 also employs a rotating tube similar to that shown at 15 in Fig. 1, but obtains a difference in phase of 180 degrees between the two directions of transmission rather than a one-way effect. This is accomplished by using a longer rotating tube section 21 designed to rotate the plane of polarization 90 degrees, and by orienting the rectangular sections 24 and 25, on either side of converters 22 and 23, at 90 degrees to one another. The twisted acoustic channel 26 is a normal reciprocal circuit element and merely serves to align one terminal acoustic channel 27 with the opposite terminal channel 25.

The group of figures, 4A to 4E, inclusive, is a schematic representation of the shifts in plane of polarization of the transverse acoustic waves traveling through the acoustic gyrator of Fig. 3, and show how the 180 degree difference in phase shift between the two directions of transmission is obtained. The vector X represents the polarization of the waves traveling through the system from left to right, as shown in Figs. 4A to 4E, and the vector Y represents the plane of polarization of the waves traveling through the system from right to left, as shown in Figs. 4E, 4D, 4C, 4B and 4A taken in that order, with the individual vectors indicating the plane of polarization as the wave emerges from each element shown in each case as viewed from channel 27. Note that for the same distance of transmission the plane of polarization of the transverse acoustic wave traveling from right to left is rotated 180 degrees at channel 27 as compared with its plane of polarization at channel 25 while the plane of polarization of the wave traveling from left to right is unchanged. This plane of polarization shift of 180 degrees for only one direction of transmission results in a reversal of phase, or a difference in phase shift of 180 degrees for one direction of transmission, as compared with the opposite direction of transmission. Thus, if there is a phase shift ϕ for one direction of acoustic transmission, the phase shift for the opposite direction of transmission is $\phi + 180$ degrees.

As set forth hereinbefore, an electrical network having these properties has been termed a "gyrator"; the term "acoustic gyrator" will therefore be employed to describe devices having the properties of the device of Fig. 3. Illustrative examples of the use of this type of device will be set forth in connection with the detailed description of Figs. 6 and 7.

Another device which may be used to perform the same function as the rotating tube of Figs. 1 and 3 is shown in Fig. 5. In this case an insulating tube 31 containing a polar liquid 32, such as nitrocellulose in solution, nitrobenzene, or nitropolystyrene, is substituted for either of the tubes 15 or 21 of Figs. 1 and 3. The tube 31 is provided with acoustically transparent diaphragms at both ends to facilitate the transition from the gaseous to the fluid transmission medium. Polar liquids of the type mentioned above contain large molecules, each of which possesses a residual dipole moment or unbalanced distribution of charge. This means that these elongated polar molecules can be oriented in a given direction by an electric field. The two pairs of plates 33—34 and 35—36, which enclose the tube 31 throughout its length, are energized with alternating voltages 90 degrees out of phase, from the high frequency oscillator 37, in much the same manner as in conventional oscilloscope deflection circuits, and thus apply a rotating electric field to the polar fluid. The rotating electric field causes rotation of the molecular dipoles, which, in turn, rotates the

plane of polarization of a polarized transverse acoustic wave traveling down the tube 31 in the fluid 32. The alternating current electrical source may be adjusted in frequency to accommodate polar fluids having various rotational viscosities, and the tube 31 must be of sufficient length to provide the desired angular plane of polarization rotation at the frequency of the electrical source. The reason for this plane of polarization rotation is the rotation of the constituent portions of the fluid 32 corresponding to the rotation of the sound transmission medium within the rotating tubes of Figs. 1 and 3. From another aspect, this phenomenon is analogous to the non-reciprocal Faraday effect, in which rotation of plane polarized light traveling in certain substances parallel to a magnetic field is believed to be caused by the precession of individual molecules in situ as a result of the applied magnetic field.

Considering the devices shown in Figs. 1, 3 and 5, it may be noted that both the rotating tube and the rotating electric field involve the application of a rotating polarizing force to the sound transmission medium to create a disturbance therein which is asymmetric with respect to the two directions of transmission. Furthermore, it is this asymmetric disturbance which favors the non-reciprocal transmission of sound waves passing through the disturbed medium in the two directions.

Although the device of Fig. 1 is a moderately simple one-way device, under certain circumstances it might be desirable to use the one-way transmission circuit illustrated in Fig. 6. As illustrated in Fig. 6, two acoustic transmission channels 41 and 42 are connected by parallel branch channels 43 and 44. Although both of these parallel channels are of the same effective length, the lower channel (44) is a normal reciprocated acoustic channel, while the upper channel (43) includes a gyrator 45, which introduces a differential 180 degree phase shift for transmission to the left, from channel 42 to 41. For the branch channels to have the same effective length, channel 44 may have to be of a somewhat different length than the portion of channel 43 external to the gyrator. In over-all transmission from right to left, therefore, the wave transmitted through the reciprocal channel 44 is 180 degrees out of phase with that transmitted through branch 43 when they recombine in channel 41, and they completely cancel each other. For transmission from left to right, however, both branches 43 and 44 are acoustically the same and the waves traveling in the two branches reinforce after the junction with channel 42.

Another illustrative use for an acoustic gyrator is shown in Fig. 7. In this figure, the plate 51 represents a wall of an acoustic chamber having an acoustic channel 54 extending therefrom, and in which it is desired to replace the acoustic impedance of the rigid plate 56 with that of an open-ended tube. To accomplish this purpose a gyrator 55 is inserted in the channel 54. Assuming an ideal acoustic gyrator to simplify the present analysis, there will be no change in the acoustic waves transmitted to the right through the gyrator as compared to the situation before its insertion. The waves reflected from the rigid wall 56, however, will be shifted in phase by 180 degrees as they retransverse the gyrator 55, which would correspond to a 180 degree shift in reactive acoustic impedance at the wall 56. The action of the gyrator may also be thought of as inverting or gyrating the acoustic impedance of the rigid plate into that of an open-ended tube just as an electrical gyrator makes a condenser beyond it appear to be an inductance.

A copending application of W. E. Kock, Serial No. 366,820, filed July 8, 1953, is also directed to devices employing transverse acoustic waves.

It is to be understood that the above-described arrangements are merely illustrative of the principles of the invention. Other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A one-way acoustic transmission system comprising first and second spaced, axially aligned, polarization selective, rectangular, acoustic channels with one of said channels being angularly shifted by 45 degrees about their common axis with respect to the other; two spaced rectangular-to-round transition channels aligned with and extending inwardly from said two spaced rectangular channels; and a rotatable acoustic tube for rotating the enclosed sound transmission medium interconnecting said two transition channels; whereby planes of polarization of transverse acoustic waves from said rectangular channels are rotated in traversing said rotatable tube, and can pass through said acoustic system in but one direction.
2. In an acoustic wave transmission system, first, second and third serially connected acoustic wave transmission channels, a sound wave transmitting medium in said second or intermediate channel, means for rotating constituent portions of said sound wave transmitting medium in one direction, and an electro-acoustic transducer coupled to one of said first and third wave transmission channels.
3. In an acoustic transmission system a first acoustic transmission channel, an acoustic gyrator coupled to said first transmission channel, and a second acoustic transmission channel coupled to said acoustic gyrator, whereby there is a difference in phase shift of 180 degrees between the two directions of transmission.
4. An acoustic transmission system as defined in claim 3 wherein said gyrator includes a sound wave transmission medium interconnecting said first and second transmission channels, and means for rotating constituent portions of said sound wave transmission medium.
5. An acoustic transmission system as defined in claim 3 wherein said gyrator includes a sound wave transmission medium interconnecting said first and second transmission channels, and means for applying a rotational force to said sound transmission medium.
6. In an acoustic wave transmission system, a first polarization selective acoustic transmission channel, an intermediate acoustic transmission region coupled to said first channel and including means for rotating the plane of polarization of the polarized sound wave in the same sense irrespective of the direction of transmission there-through, and a second acoustic transmission channel including polarization discriminating means, coupled to said intermediate region.
7. In combination, a first acoustic transmission channel, an acoustic transmission medium coupled to said first channel, means applying a rotational force to said medium whereby said transmission medium becomes non-reciprocal, and a second acoustic transmission channel coupled to said medium and forming a series acoustic path from said first channel through said medium to said second channel, and an electro-acoustic transducer coupled to one of said acoustic transmission channels.
8. An acoustic mode converting coupling comprising a first acoustic channel, adapted for the transmission of longitudinal sound waves of a particular frequency; a second elongated closed acoustic channel having a rectangular cross-section, adapted for the transmission of transverse acoustic waves; said first channel being coupled to said second channel by means of an aperture in the side of said second channel which is small with respect to a wavelength at the frequency of operation; and means for enhancing the propagation of transverse acoustic waves in said second acoustic channel.
9. An acoustic system as defined in claim 8 in which said means constitutes an adjustable piston located in said second channel adjacent said aperture.
10. An acoustic system as defined in claim 8 in which an acoustic wave generator is coupled to said first channel.
11. An acoustic system comprising a sound source having a predetermined frequency, an elongated closed acoustic channel having a rectangular cross-section and

having an aperture in a side thereof which is small with respect to the wavelength of sound at said frequency, means coupling said sound source to said aperture, and means for enhancing the propagation of transverse acoustic waves in said acoustic channel.

12. An acoustic system comprising a sound source having a predetermined frequency, a first acoustic channel having an aperture in a side thereof which is small with respect to the wavelength of sound at said frequency, means coupling said sound source to said aperture, an acoustic gyrator coupled to said first transmission channel, and a second acoustic transmission channel coupled to said acoustic gyrator, whereby there is a difference in phase shift of 180 degrees between the two directions of transmission through said acoustic system.

13. An acoustic system comprising an elongated rectangular acoustic channel having broad and narrow inner cross-sectional dimensions, and having an aperture in one of said narrow sides, and an acoustic wave generating source of a predetermined frequency and wavelength coupled to said aperture, the half wavelength of the generated waves being greater than said narrow but less than said broad dimension of said rectangular guide.

14. An acoustic mode converting coupling comprising a first acoustic channel, a sound source radiating directly into said first acoustic channel, a second elongated closed acoustic channel having a rectangular cross-section coupled to said first channel, and mode-selective means in said second channel for enhancing the propagation of transverse acoustic waves and for suppressing undesired modes.

15. An acoustic system as defined in claim 14 in which said mode-selective means is a piston located in said second channel.

16. An acoustic system comprising a source of polarized transverse acoustic waves, and an acoustic wave plane-of-polarization rotator coupled to said source of acoustic waves, said rotator comprising a rotatable acoustic tube for rotating the enclosed sound transmission medium, whereby the polarization of the transverse acoustic waves is rotated in traversing said acoustic tube.

17. In an acoustic wave transmission system first, second and third serially connected acoustic wave transmission channels, a sound wave transmission medium in said second or intermediate channel, means for rotating constituent portions of said sound wave transmission medium in one direction, and means coupled to each of said first and third channels for favoring the transmission of transverse acoustic waves of a particular mode.

18. In combination, an elongated closed acoustic transmission channel having a transverse aperture adjacent one end, means for applying acoustic energy of a pre-

assigned frequency to said aperture, and an end-wall closing said end of said acoustic channel, the distance from said aperture to said end-wall being an integral number of half wavelengths of a transverse acoustic mode in said transmission channel at said preassigned frequency.

19. An acoustic system comprising a source of polarized transverse acoustic waves, a medium for transmitting transverse acoustic waves coupled to said source, and means for rotating said medium whereby the polarization of the transverse acoustic waves is rotated in traversing said medium.

20. In an acoustic transmission system, a first acoustic transmission channel, means for providing polarized acoustic waves in said channel, an acoustic wave polarization rotator coupled to said first transmission channel, a second acoustic transmission channel coupled to said acoustic wave polarization rotator, and an electroacoustic transducer coupled to one of said acoustic transmission channels.

21. In combination, a source of polarized acoustic waves and an acoustic wave polarization rotator coupled to said source, said polarization rotator having a length equal to

$$\frac{\theta}{360} \times \frac{c}{n}$$

where θ equals 90 degrees, c is the velocity of sound in the rotator, and n is the angular velocity in revolutions per unit time of the polarized acoustic waves in said rotator.

22. In combination, a source of polarized acoustic waves and an acoustic wave polarization rotator coupled to said source, said polarization rotator having a length equal to

$$\frac{\theta}{360} \times \frac{c}{n}$$

where θ equals 45 degrees, c is the velocity of sound in the rotator, and n is the angular velocity in revolutions per unit time of the polarized acoustic waves in said rotator.

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