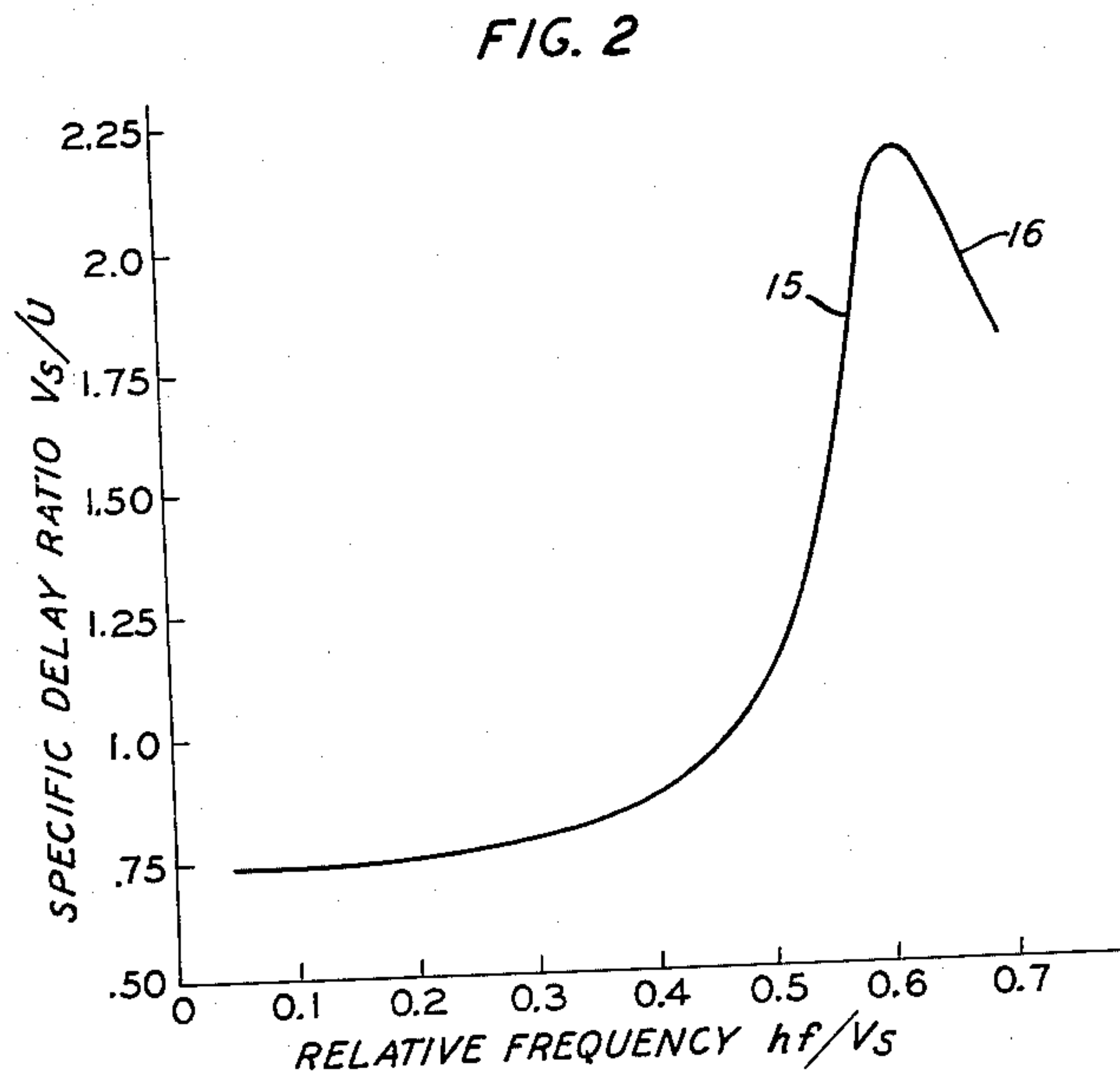
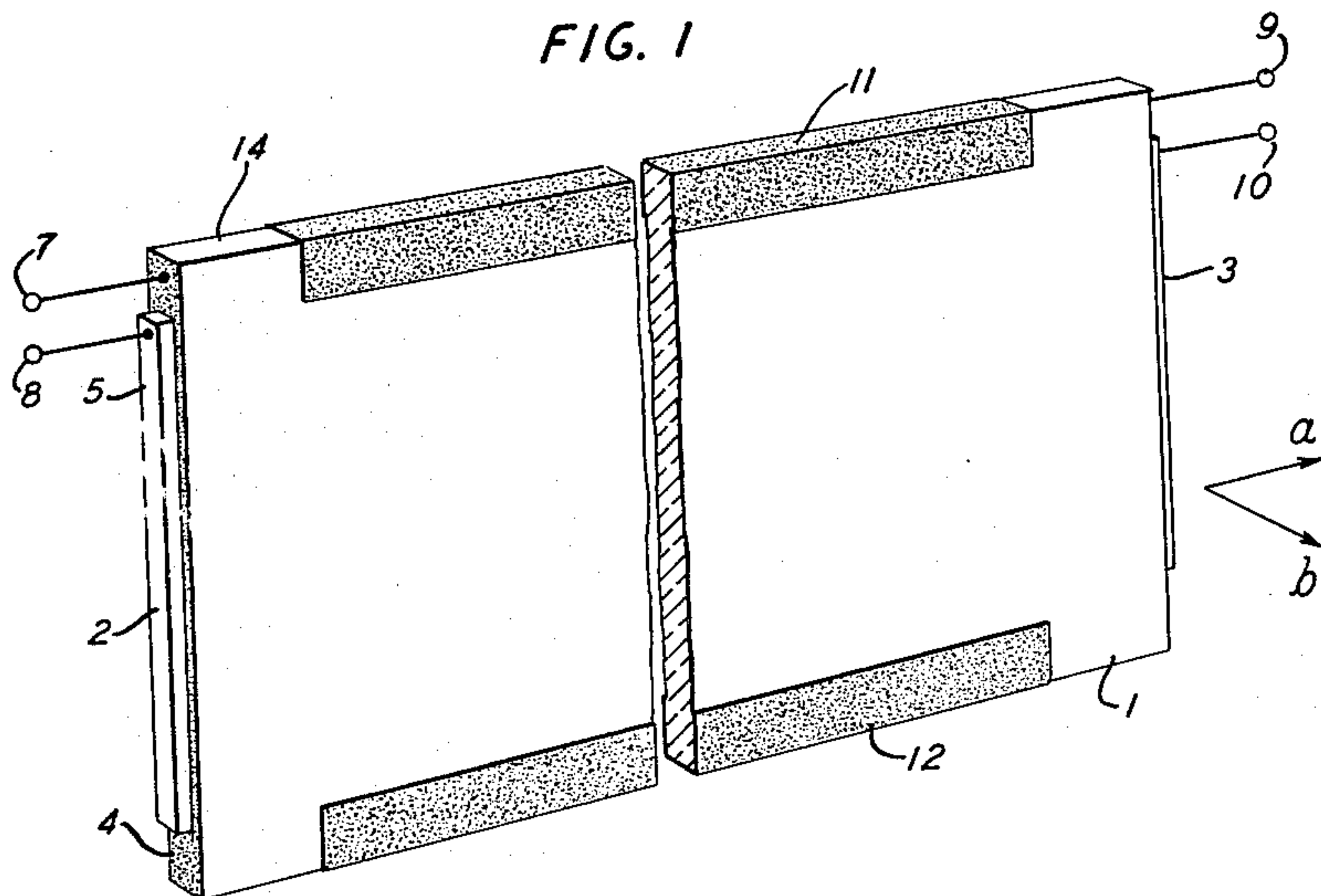


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NONDISPERSIVE ULTRASONIC DELAY LINE USING DELAY MEDIUM  
CONSISTING OF CUBIC SYMMETRY CRYSTAL HAVING  
PARTICULAR ORIENTATION  
Filed April 27, 1962



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## 3,259,858 NONDISPERSIVE ULTRASONIC DELAY LINE USING DELAY MEDIUM CONSISTING OF CUBIC SYMMETRY CRYSTAL HAVING PAR- TICULAR ORIENTATION

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This invention relates to wave transmission and more particularly to ultrasonic delay lines of the electromechanical type.

An object of the invention is to delay an electric signal in a predetermined manner over a wide band of frequencies. More specific objects are to lower the loss and reduce the distortion incident to delaying the signal.

A delay line comprising a strip of polycrystalline metal with appropriate electromechanical transducers at its ends will operate satisfactorily up to frequencies of about three megacycles per second. Above this range, the grain structure of the metal causes scattering which increases the loss and the distortion to unacceptable amounts. A plate cut from a single crystal does not have grain boundaries and is thus more satisfactory for use at the higher frequencies. However, for optimum performance, I have found that the longitudinal axis and the thickness dimension of the plate must each correspond in direction with a direction of pure longitudinal wave motion in the crystal. Either a symmetrical or an antisymmetrical mode of guided wave propagation may be used to transmit the signal waves along the strip. The resultant delay characteristic may be either dispersive or non-dispersive. The upper frequency of the practical operating range is limited by fabrication techniques rather than material properties. Lines operating at frequencies up to 50 megacycles appear to be practical at present.

The nature of the invention and its various objects, features, and advantages will appear more fully in the following detailed description of a typical embodiment illustrated in the accompanying drawing, of which

FIG. 1 is a perspective view of an ultrasonic delay line in accordance with the invention; and

FIG. 2 is a typical delay-versus-frequency characteristic obtainable with the structure shown in FIG. 1. The ordinates and abscissas are plotted in dimensionless units.

In FIG. 1, an elongated plate 1, with a width at least ten times the thickness has the electromechanical transducers 2 and 3 fastened to its respective ends. As disclosed in more detail in my copending application Serial No. 824,437, filed July 1, 1959, the desired guided mode of propagation involves only the major surfaces of the plate. In general, interaction of the motion in the strip with the minor surfaces has undesirable effects such as the generation of spurious effects. The condition of having a plate width ten or more times the thickness makes it possible to transmit most of the energy in the mechanical wave motion free from interaction with the minor surfaces. Each of the transducers is in the form of a bar of piezoelectric material, such as barium titanate ceramic, with electrodes on opposite sides. One of the electrodes 4 is applied to the end of the plate 1 and the other electrode 5 is applied to the opposite side of the transducer 2. The input terminals 7 and 8 are connected, respectively, to the electrodes 4 and 5. The output terminals 9 and 10 are connected, respectively, to similarly placed electrodes associated with the transducer 3 at the other end of plate 1. Acoustic absorbing material in the form of adhesive tape is applied to the edges of the plate 1, as shown at 11 and 12, to reduce energy reflection at the minor surfaces 14.

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The plate 1 is cut from a single crystal. The direction of the longitudinal axis, indicated by the arrow *a*, and the direction of the thickness dimension, indicated by the arrow *b*, each correspond with a direction of pure longitudinal wave motion in the crystal from which the plate 1 is cut.

The reason why both the thickness dimension and longitudinal axis of plate 1 must both correspond to possible directions of pure longitudinal wave motion will be understood when it is recognized that the guided mode that is conventionally called the longitudinal mode in thin plates is actually a composite wave motion made up of both plane longitudinal and plane transverse waves travelling at angles to the plate axis and reflecting from the major surfaces. Thus in order to maintain the desired symmetry of the total wave motion, the normal to the medium plane must also coincide with a direction of pure longitudinal wave motion even though the nominal direction of propagation of the total wave motion is along the axis. It is understood therefore that the term "direction of pure longitudinal wave motion" has reference to the direction in which such motion is capable of support in the unbounded crystal material before the crystal is shaped into the plate.

The directions of pure longitudinal wave motion have been found for all systems of crystal symmetry. For example, the paper by F. E. Borgnis entitled "Specific Directions of Longitudinal Wave Propagation in Anisotropic Media," published in Physical Review, vol. 98, No. 4, May 15, 1955, pages 1000 to 1005, outlines a general method for finding the complete set of directions along which pure longitudinal waves can be propagated in an anisotropic medium. The author applies the method to the trigonal, hexagonal, tetragonal, and cubic systems of crystal symmetry, and enumerates the specific directions of pure longitudinal wave motion.

The orientation of the plate in a coordinate system formed by the crystallographic axes X, Y, and Z associated with a crystal medium can be specified by giving the directions of the lines *a* and *b* associated, respectively, with the length and thickness directions of the plate. In specifying the direction of a line or vector, we will use the common convention of giving the three direction cosines of the line. In agreement with the notation of Borgnis, *l*<sub>1</sub>, *l*<sub>2</sub>, and *l*<sub>3</sub> are the direction cosines formed between a vector and the X-, Y- and Z-axes, respectively. These will be given in the order (*l*<sub>1</sub>, *l*<sub>2</sub>, *l*<sub>3</sub>).

Three examples of the proper orientation of the longitudinal direction *a* and the thickness direction *b* for a plate 1 cut from a single crystal having cubic symmetry, such as silicon or germanium, are the following:

Case 1.—The directions *a* and *b* may coincide, respectively, with any two of the X-, Y-, and Z-axes of the crystal.

Case 2.—The direction cosines of the direction *a* are ( $1/\sqrt{2}$ ,  $1/\sqrt{2}$ , 0) and the direction cosines of the direction *b* are ( $-1/\sqrt{2}$ ,  $1/\sqrt{2}$ , 0).

Case 3.—The direction cosines of the direction *a* are ( $1/\sqrt{3}$ ,  $1/\sqrt{3}$ ,  $1/\sqrt{3}$ ) and the direction cosines for the direction *b* are ( $-1/\sqrt{2}$ ,  $1/\sqrt{2}$ , 0).

Of course, other combinations that are crystallographically equivalent to the cases given may be used.

If the transducer 2 is poled to vibrate in the direction *a* when an electric signal is impressed upon the terminals 7 and 8, a symmetrical guided mode will be set up in the plate 1. The transducer 3 will, of course, be adapted to reconvert the symmetrical vibrations in the plate 1 to electrical variations at the output terminals 9 and 10. FIG. 2 shows a typical dimensionless characteristic for the first symmetrical mode in a plate 1 of silicon with the orientation given above under Case 1.



The ordinates represent the specific delay ratio, which is the ratio of the velocity  $V_s$  of a shear wave motion along a cube axis to the group velocity  $U$ . The abscissas are the product of the thickness  $h$  and the frequency  $f$  divided by  $V_s$ .

At the lower relative frequencies, the curve is substantially straight and single-valued, providing a non-dispersive delay characteristic. In the neighborhoods of the points of inflection 15 and 16, the curve is approximately linear, with a positive and a negative slope, respectively. This type of characteristic is useful in the design of delay networks intended for applications involving pulse expansion or compression. Other regions can be found where the curvature is either positive or negative, as may be required.

To obtain an antisymmetrical guided mode in the plate 1, the transducer 2 is poled parallel to the direction  $b$  in FIG. 1. With the applied field in the direction  $a$  at right angles to  $b$ , a thickness-shear mode of vibration is set up in the transducer, which excites and responds to the antisymmetrical guided mode in the plate 1.

What is claimed is:

1. A delay line comprising a thin, elongated plate, with a width at least ten times the thickness, and an electromechanical transducer associated with one end thereof, the plate being cut from a single crystal having a cubic system of symmetry and three mutually perpendicular crystallographic axes X, Y, and Z, the plate having a length dimension with direction cosines  $(1/\sqrt{2}, 1/\sqrt{2}, 0)$  with respect to X, Y, and Z and a thickness dimension with direction cosines  $(-1/\sqrt{2}, 1/\sqrt{2}, 0)$  with respect to X, Y, and Z.

2. A delay line comprising a thin, elongated plate, with a width at least ten times the thickness, and an electromechanical transducer connected to one end thereof, the plate being cut from a single crystal having a cubic system of symmetry and three mutually perpendicular crystallographic axes X, Y, and Z, the plate having a length dimension with direction cosines  $(1/\sqrt{3}, 1/\sqrt{3}, 1/\sqrt{3})$  with respect to X, Y, and Z, and a thickness dimension

sion with direction cosines  $(-1/\sqrt{2}, 1/\sqrt{2}, 0)$  with respect to X, Y, and Z.

3. A delay line comprising a thin elongated plate being cut from a single crystal that has a cubic system of symmetry and a width at least ten times its thickness, and electromechanical transducers associated with the respective ends thereof; said plate having its length dimension extending in a direction capable of supporting pure longitudinal wave motion in said crystal before said plate is cut selected from the group of crystallographic directions consisting of directions corresponding to crystallographic axes of said crystal, directions having direction cosines  $(1/\sqrt{2}, 1/\sqrt{2}, 0)$  with respect to said axes and directions having direction cosines  $(1/\sqrt{3}, 1/\sqrt{3}, 1/\sqrt{3})$  with respect to said axes; said plate having its thickness dimension extending in a direction capable of supporting pure longitudinal wave motion in said crystal before said plate is cut selected from the group of crystallographic directions consisting of directions corresponding to the crystallographic axes of said crystal, directions having direction cosines  $(-1/\sqrt{2}, 1/\sqrt{2}, 0)$  with respect to said axes; and directions having direction cosines  $(-1/\sqrt{2}, 1/\sqrt{2}, 0)$  with respect to said axes.

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