

[54] ULTRASONIC DELAY LINES

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[51] Int. Cl. H03h 9/30

[58] Field of Search 333/30 R, 30 M, 71, 333/72, 32

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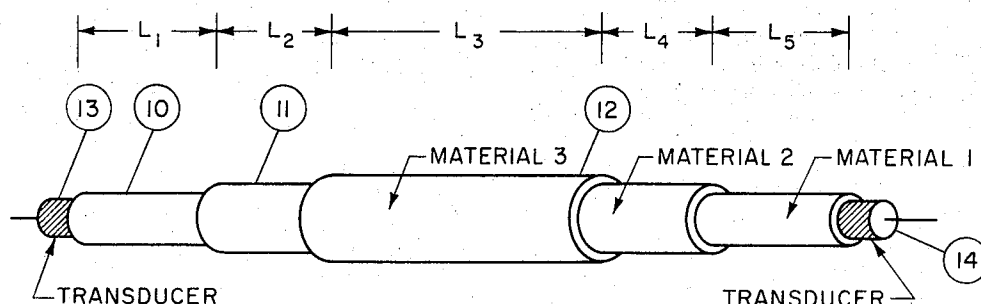
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[57]

ABSTRACT

Delay lines with a variety of delay versus frequency characteristics are obtained by fabricating the delay line apparatus from multilayer materials. In one modification, the delay line is of rod construction and in another, of strip design.

3 Claims, 7 Drawing Figures



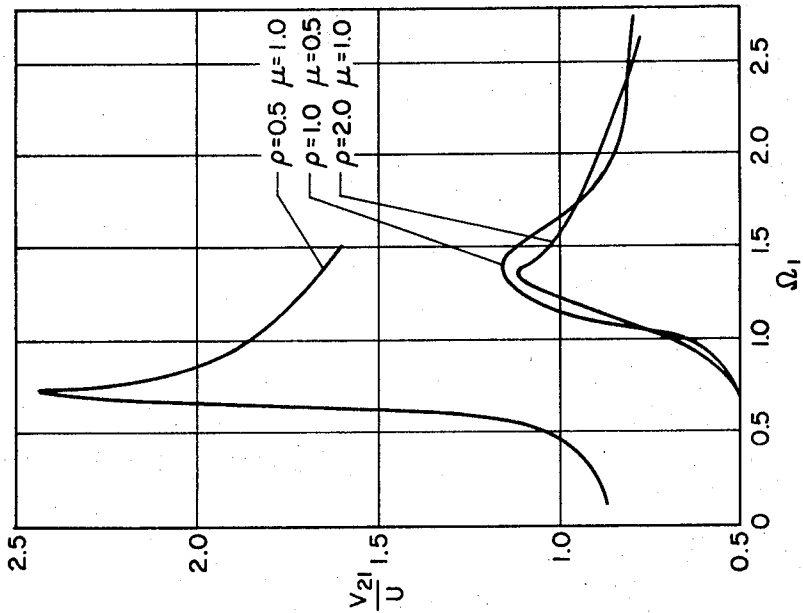


Fig. 1

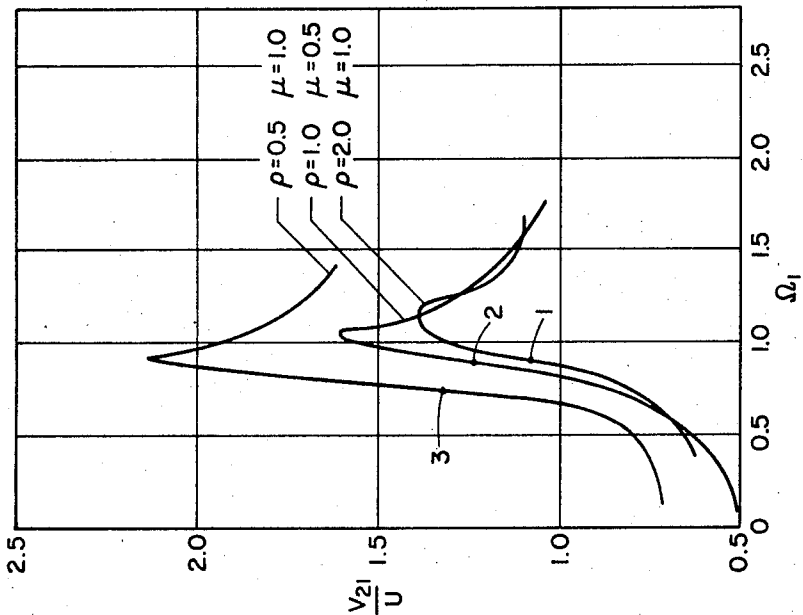


Fig. 2

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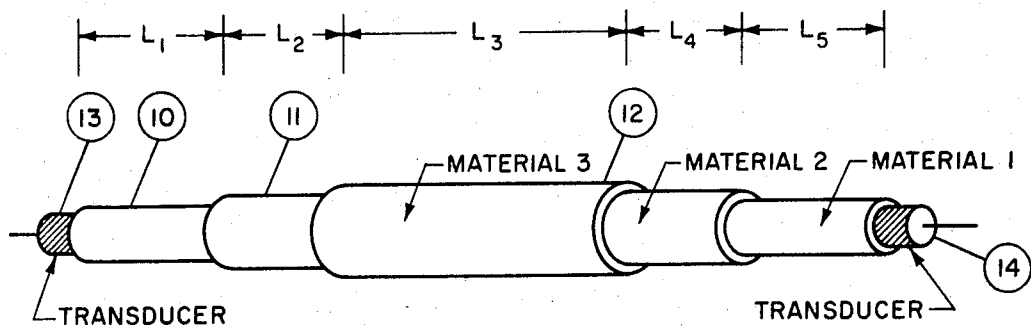


Fig. 3

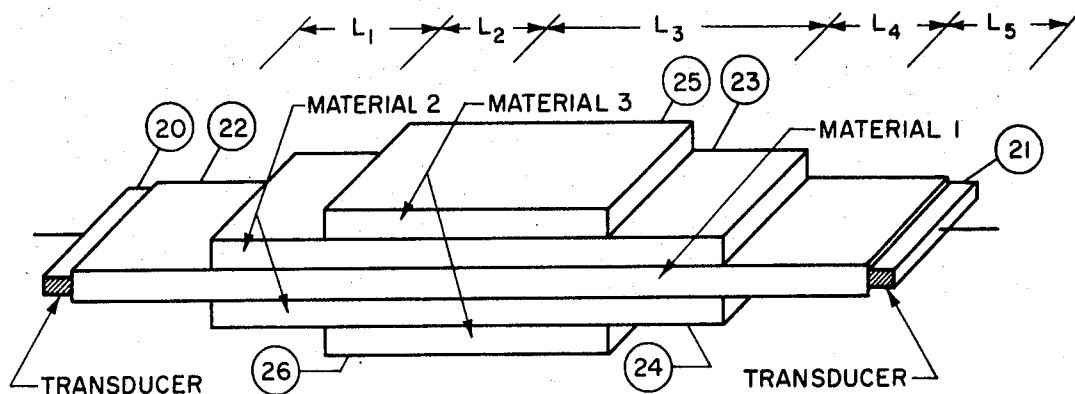


Fig. 4

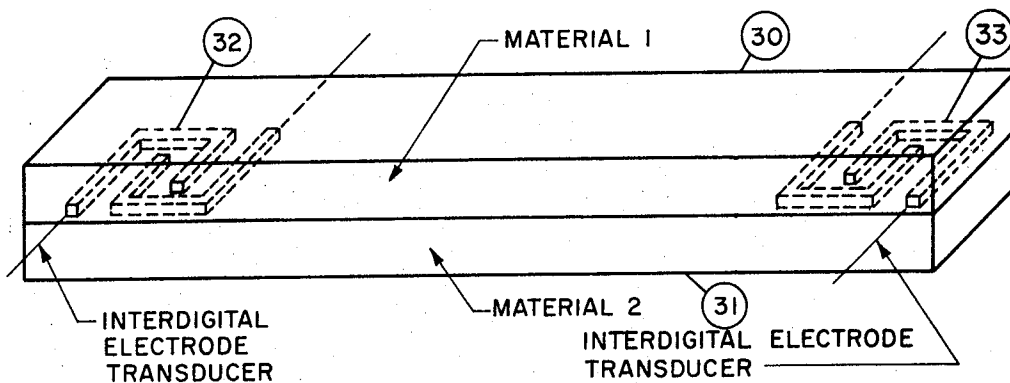


Fig. 6

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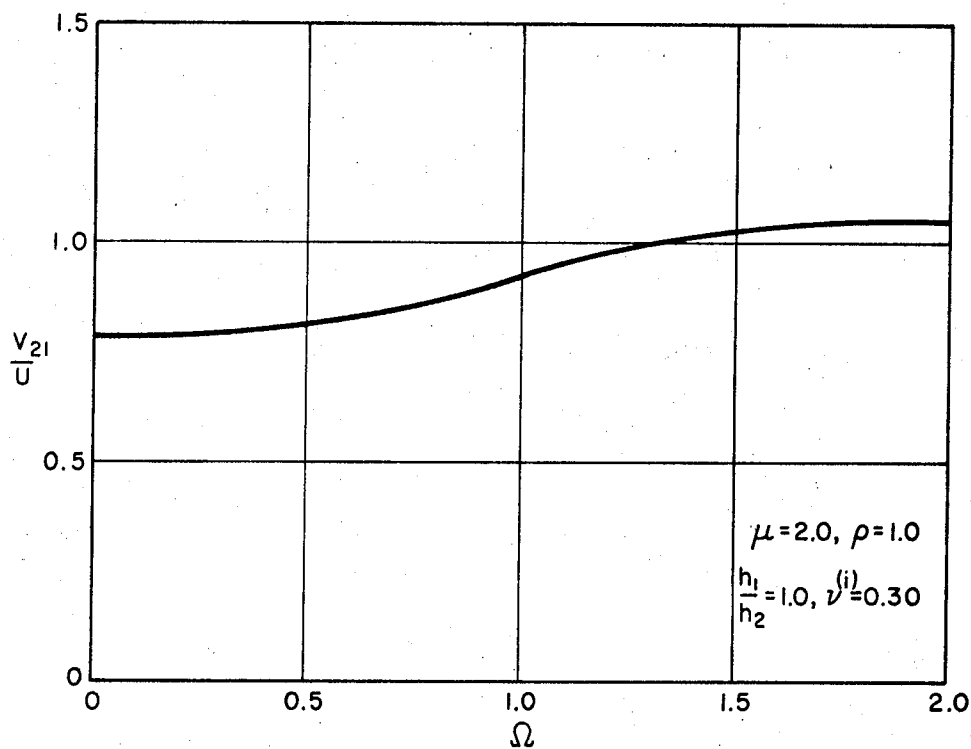


Fig. 5

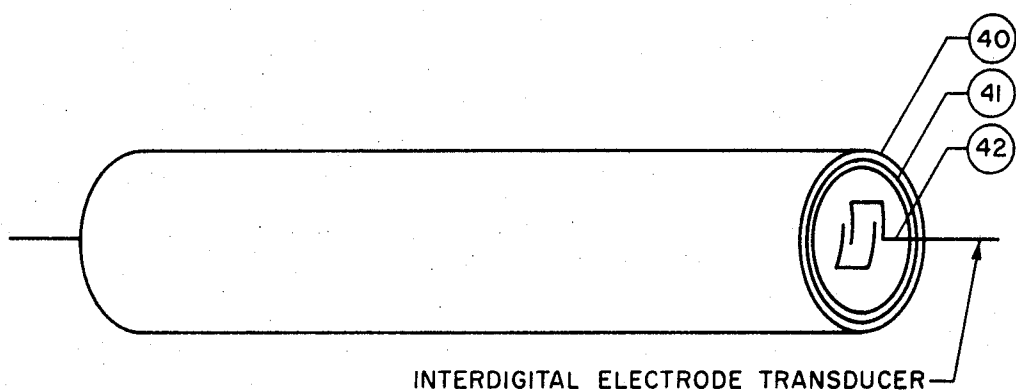


Fig. 7

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ULTRASONIC DELAY LINES

The present invention relates generally to electroacoustic apparatus and, more particularly, to guided wave delay lines of the dispersive and nondispersive type wherein the delay versus frequency characteristic may have a range of possible slopes or curvatures.

In the conventional acoustic delay line, a piezoelectric transducer transforms an electrical signal into a mechanical deformation which then propagates as an elastic wave along a prescribed path through the delay medium. In the usual case, such as the simple rod-type delay line, the elastic wave propagates essentially as a plane wave in an infinite medium, free from any surface interactions.

In the guided wave acoustic delay line, the cross-sectional dimensions of, for example, a wire or a rectangular strip are so chosen relative to the wavelength that the elastic wave interacts strongly with the boundary surfaces and propagates as a guided elastic wave motion. Thus, there exists many possible modes of wave propagation and, in most of these modes, the phase velocity varies as a function of frequency. In this sense, the delay lines utilizing these modes are termed "dispersive."

There are, however, exceptions to the above in the case of zeroth-order modes corresponding to thickness shear in a thin, rectangular strip and torsional in a small diameter rod. These zeroth-order modes are nondispersive and, below the cut-off frequency of the lowest dispersive mode, they propagate as isolated modes of elastic wave motion. These last two modes thus can operate without an objectionable signal distortion up to this cut-off frequency. Additionally, the low velocity of propagation of the torsional mode, as compared for example, to the first longitudinal mode, renders this mode most suitable for nondispersive delay lines where long delay times in the order of milliseconds are required.

One of the most important applications of a dispersive guided wave delay line with a linear delay characteristic is in radar systems for increasing the range without necessitating a corresponding increase in peak power. In the usual pulse radar system, range is increased by increasing the average power radiated while range resolution is increased by decreasing the pulse length. To increase range without compromising resolution requires an increase in peak power which is ultimately limited by voltage breakdown in the system. One solution to this problem involves the pulse compression system which operates on the basis that when a short pulse is transmitted to a linear delay network of positive slope the various components of the Fourier frequency spectrum of the pulse are linearly dispersed in time, the higher frequencies being delayed more than the lower frequencies. The output is a linearly frequency modulated pulse with an amplitude distribution described by the function $\sin x/x$. Thereafter, this pulse, when it is returned, for example, from a remote reflecting target, may be transmitted to a second delay network having an equal but negative slope so that the components of the frequency spectrum will be delayed in inverted order, that is, the higher frequencies being delayed less than the lower frequencies. Alternatively, the pulse may be compressed by retransmission through the same delay line used for expanding the original pulse, provided the order of the frequency is inverted by modulating with a local oscillator fre-

quency of twice the midband frequency of the input pulse and selecting the lower sideband of the modulation products. After such processing, it will be recognized, the frequency components are restored to their initial phase relationship and the output pulse will have the same shape as the input pulse.

In designing a dispersive delay line, made, for example, of a rod of a given material, the thickness of the rod must be chosen so that the inflection point of the delay versus frequency curve occurs at a certain frequency. The linearity and the slope of this curve may be altered by changing the delaying material. But once the material is selected, the delay characteristic may be altered only by changing the length of the rod or by subdividing it into a series of lengths of different thicknesses. Thus, dispersive delay lines made of a single material have somewhat inflexible delay versus frequency characteristics.

It is accordingly a primary object of the present invention to provide a dispersive delay line with a linear delay versus frequency characteristic whose slope may be readily selected within a range of possible values.

It is another object of the present invention to provide a dispersive delay line with a nonlinear delay versus frequency characteristic of a desired curvature.

Another object of the present invention is to provide a dispersive delay line operating in the zeroth torsional mode in rods or in the zeroth face shear mode, in thin rectangular strips.

Another object of the present invention is to provide a nondispersive delay line which is capable of delaying high frequency signals wherein the acoustic signal is propagated as an interface disturbance.

Other objects, advantages and novel features of the invention will become apparent from the following detailed description of the invention when considered in conjunction with the accompanying drawings wherein:

FIG. 1 is a family of curves showing the variations of the specific group delay with frequency for rods of different materials;

FIG. 2 is a plot of the same rods but with a different ratio of core thickness to casing thickness;

FIG. 3 illustrates one modification of the invention wherein the delay line is composed of concentric, cylindrical members;

FIG. 4 shows an alternative construction utilizing multilayered, rectangular strips;

FIG. 5 shows the variation of the specific group delay with frequency of waves traveling in the zeroth face shear mode in a structure like that of FIG. 4;

FIG. 6 shows an alternative arrangement wherein the mechanical deformation is in the form of a Stoneley wave; and

FIG. 7 shows a delay line wherein the mechanical deformation is in the form of a Rayleigh wave.

Briefly and in general terms, the objects of the invention enumerated above are realized by fabricating the delay line apparatus from multilayer materials instead of the unitary material heretofore employed in prior art structures. With multilayer materials, it will be appreciated, a broader choice of design parameters are available and a greater selection of delay versus frequency characteristics may be obtained. Thus, in one modification, the delay line consists of a plurality of concentric, cylindrical members made from different materials. The geometrical and physical properties of the individual members may be selected to yield the performance

curves desired. In an alternative embodiment, a plurality of rectangular strips are utilized to achieve the same flexibility. The first construction is utilized with waves traveling in the zeroth torsional mode or in the first axisymmetric, nontorsional mode. The second construction is utilized with waves propagating in the zeroth face shear mode or in the first longitudinal mode.

Referring now to FIG. 1, the various curves shown illustrate the variation of the specific group delay with frequency of waves traveling in the first axisymmetric, nontorsional mode in a composite rod consisting of a circular core of one material bounded by and bonded to a circular casing of another material. It will be seen that all of the curves, which represent different combinations of materials having various density and stiffness ratios, ρ and μ , possess an inflection point, such as points 1, 2 and 3 in FIG. 1, and that a linear range of delay versus frequency occurs over an operating range adjacent to these points. The ratio of core thickness to casing thickness H is 4.5.

In FIG. 2 this ratio equals one-third, and it will be observed that the same combinations of materials now yield a different set of delay versus frequency curves. The inflection points are displaced from those of FIG. 1, and the linear regions occur at different frequencies.

A guided delay line making use of the above characteristics is shown in FIG. 3. The apparatus consists of a solid inner rod or core member 10 made of a first material. A shorter, circular casing 11 of a second material is bonded thereto, and still shorter length of circular casing 12 of a third material is bonded to this casing. Attached to opposite ends of the central core 10 are the piezoelectric input and output transducers 13 and 14, respectively. As is well known, the orientation and construction of these transducers and the manner in which the input transducer is excited determine the particular mode excited in the delay line.

Once the variation of delay versus frequency for a composite rod consisting of a core member of one material, having a circular casing of another material bonded thereto, such as 10 and 11, has been established, the addition of a third layer, such as 12, it will be appreciated, allows an added degree of freedom in the design of the delay line. Changing the cross section of these elements, likewise, permits the designing of dispersive delay lines having a still wider variety of delay versus frequency characteristics. This may be explained qualitatively by noting that this arrangement constitutes a series combination of cross sections and, consequently, the delay at frequency f_i of the rod assembly is given as

$$(1) \quad D(f_i) = d_{i1}L_1 + d_{i2}L_2 + d_{i3}L_3 + d_{i4}L_4 + d_{i5}L_5.$$

where d_{i1} , d_{i2} and d_{i3} are the specific delays of the various portions of the rod, at the frequency f_i ; L_1 , L_2 , L_3 , L_4 , L_5 are the lengths of the portions. The choice of the materials 1, 2, 3 and the relative thickness of the layers affects the values of the specific delays d_{i1} , d_{i2} , d_{i3} . However, the delay versus frequency characteristic will also depend upon the lengths L_1 , L_2 , L_3 , L_4 , L_5 .

The individual components of the delay line may be made of any material which is suitable for acoustic delay media, such as, for example, aluminum, nickel-iron alloy, iron, fine grained bronze or any other fine grained material.

It has been determined by mathematical analysis that the zeroth torsional mode in a multilayer rod arrangement, such as shown in FIG. 3, is dispersive. This same mode in a unitary rod, it will be recalled, is nondispersive. Consequently, this zeroth torsional mode with its advantages of low signal distortion and low velocity of propagation may be utilized to provide a new class of dispersive guided wave delay lines.

In FIG. 4 there is disclosed an analogous multilayer guided wave delay line fashioned from a plurality of relatively thin, rectangular strips of different metal. Here, the piezoelectric input and output transducers 20 and 21 are secured to opposite end faces of an inner rectangular strip 22. Bonded to its opposite surfaces are a first pair of shorter rectangular strips 23 and 24. A second pair of still shorter strips 25 and 26 are bonded to these strips. Each pair of strips is made of the same material so that the over-all stepped sandwich has a symmetrical configuration and composition.

It has also been determined mathematically that the zeroth face shear mode in a multilayer plate assembly, such as shown in FIG. 4, is dispersive. This, too, is in contradistinction with the same mode propagating in a unitary plate of a single material and may be utilized to provide a new class of dispersive guided wave delay lines.

It should be appreciated that the consecutive casings, where the delay line is of a rod design or the consecutive strips where the line is made of such strips, need not be of shorter length such as depicted in FIGS. 3 and 4. What is important is that the cross section of the delay medium changes along its length. It will be appreciated that the length of proportions L_1 , L_2 , L_3 , L_4 , L_5 and the materials from which these components are made will be selected in order to achieve the desired performance curve.

FIG. 5 illustrates the variation of the specific group delay with frequency of waves traveling in the zeroth face-shear mode in a three-layer plate construction of the type shown in FIG. 4.

The arrangements as shown in FIGS. 3 and 4 are capable of linearly delaying pulses having a considerably larger bandwidth than has been possible heretofore. This improvement is due to the more extensive linearity of their delay versus frequency characteristics, as exemplified by the curves of FIG. 5.

The frequencies at which nondispersive delay lines operate without objectionable signal distortion do not exceed a few megacycles. In FIG. 6 there is disclosed a composite delay line which is capable of operating at considerably higher frequencies. The apparatus consists of a two-layer, rectangular plate made by bonding together two different strips, 30 and 31, of similar dimensions. The composite plate is driven by an interdigital electrode transducer 32 which excites a Stoneley wave which propagates as an interface disturbance. The output signal is removed by a second interdigital electrode transducer 33. It will be appreciated that the individual comblike strips that form each transducer are provided with suitable insulating coatings to protect against shorting by the confronting surfaces of the two strips. One of the materials that lends itself to this type of delay line is silicon which exhibits relatively low losses in the microwave signal region.

FIG. 7 shows an arrangement in which the signal is propagated as an inner surface Rayleigh wave in a hollow cylinder made of two concentric shells 40 and

41. One of the conditions for operation is that the shear velocity in the material of the inner cylinder be smaller than in the material of the outer layer. The Rayleigh waves are produced by an interdigital electrode transducer 42 affixed to the inner wall surface of the inner shell of the hollow composite cylinder. The output signal is extracted by a similar transducer located at the other end of the cylinder.

Obviously many modifications and variations of the present invention are possible in the light of the above teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed is:

1. A solid delay line comprising, in combination,
 - a first cylindrical shell member made of a material that is capable of propagating elastic waves;
 - an input interdigital electrode transducer secured to the inner wall surface of said shell member at a position adjacent one end thereof;
 - an output interdigital electrode transducer secured to the inner wall surface of said shell member at a location adjacent the other end thereof;
 - said transducers being in alignment such that an elastic wave excited by said input transducer is subsequently detected by said output transducer;
 - a second cylindrical shell member made of a different material that is also capable of propagating elastic waves,
 - the inner surface of said second cylindrical shell member being bonded to the outer surface of said first inner cylindrical shell member over their common length,
 - the thickness of said first cylindrical shell member being such that said elastic wave also travels through portions of said second cylindrical shell member.
2. A delay line comprising in combination
 - a solid rod made of a first material that is capable of propagating elastic waves;

an input transducer secured to one end of said rod; an output transducer secured to the other end of said rod;

a first cylindrical shell member having a length less than that of said rod bonded to the outer surface of said rod,

said shell member being made of a second material that is also capable of propagating elastic waves;

a second cylindrical shell member having a length less than that of said first cylindrical shell member, said second cylindrical shell member being bonded to the outer surface of said first cylindrical shell member and being made of a material that is capable of propagating elastic waves,

The lengths of said rod, and said first and second cylindrical shell members and the density and stiffness ratios of said rod and said first and second cylindrical shell members being selected to achieve the signal time delay desired.

3. A solid delay line comprising in combination

- a pair of unequal length strips made of different metals that are capable of propagating elastic waves;
- said strips being bonded together over their common length and having a thickness such that any elastic wave excited in the longer strip travels also within the shorter strip when it reaches one end of this strip;

an input transducer secured to one end face of the longer strip;

an output transducer secured to the other end face of said longer strip;

a third strip having a length less than the longer strip of said pair and bonded to said longer strip over its length,

said elastic wave also traveling within said third strip when it reaches one end thereof;

the lengths of said strips and their density and stiffness ratios being selected to obtain the desired signal time delay.

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