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Hartmann et al.

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[54] CASCADED F. M. CORRELATORS FOR LONG PULSES

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[52] **U.S. Cl.** .....**333/30 R,** 310/9.8, 333/72

[51] **Int. Cl.**.....**H03h 7/30,** H03h 9/30

[58] **Field of Search** 333/30, 72, 6; 310/9.7, 9.8; 343/17.2

[56] **References Cited**

UNITED STATES PATENTS

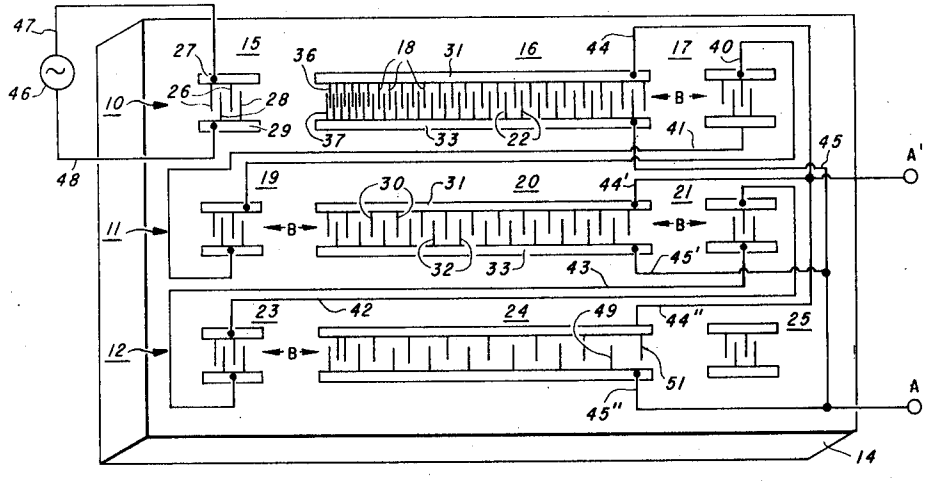
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[57] **ABSTRACT**

Methods and apparatus are disclosed for producing a frequency dispersive surface wave delay device or correlator having a large time bandwidth product. The device comprises several sections, each of which contributes a discrete frequency dispersive delay to the incident signal. These sections are cascaded together and the individual delays are additive producing a device having a large time bandwidth product. Each section comprises at least two interdigital surface wave transducers deposited on a piezoelectric substrate, at least one of the transducers having electrodes of graded periodicity. A Fourier transform computer program may be used to optimize the overall correlator characteristics by defining the optimum weighting pattern to be utilized on one or both of the transducers of each cascaded section.

9 Claims, 9 Drawing Figures



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4 Sheets-Sheet 1

Fig. 1

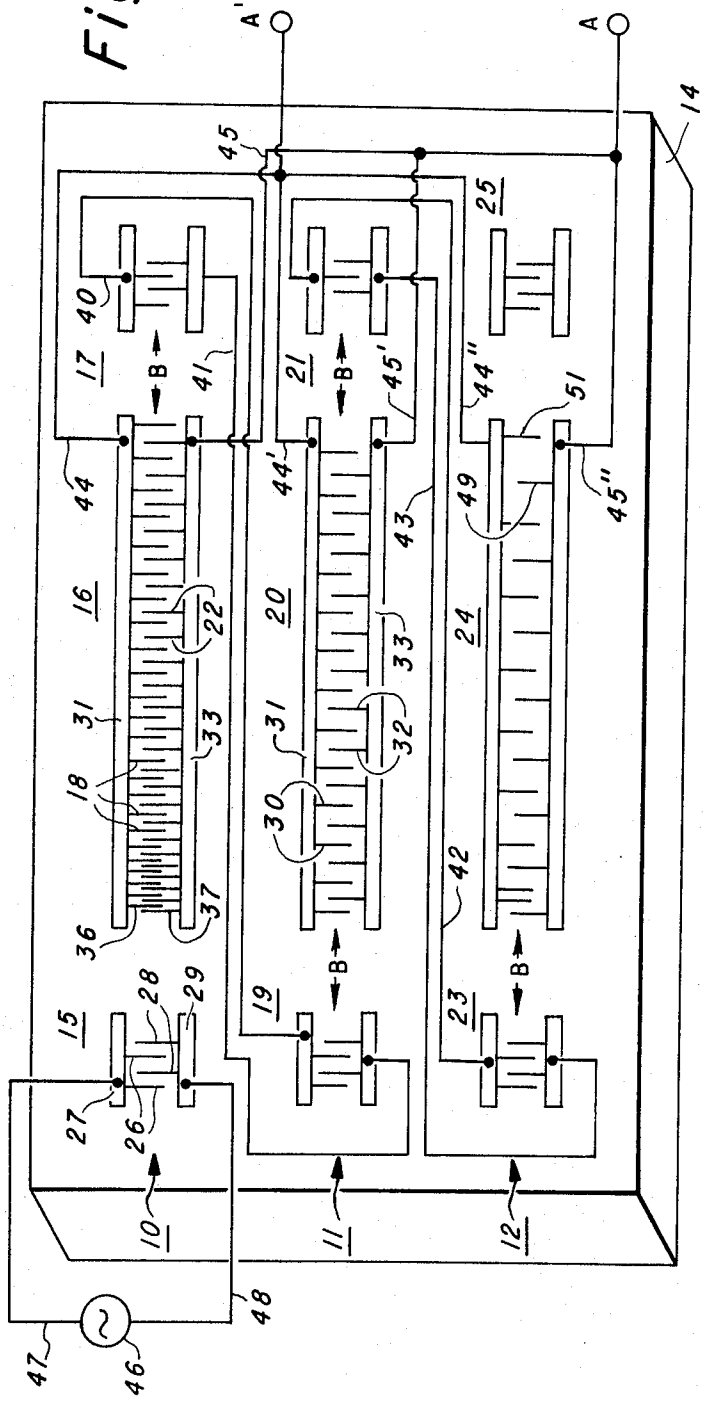


Fig. 3

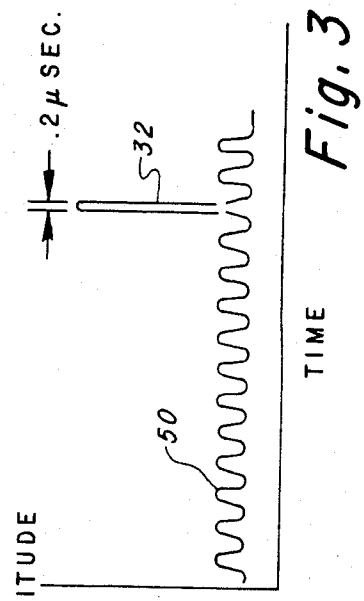
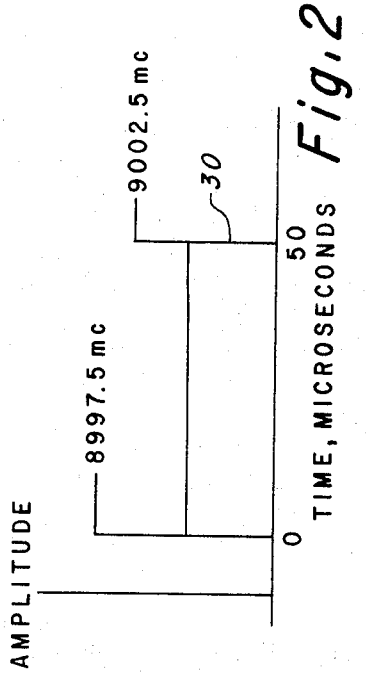


Fig. 2



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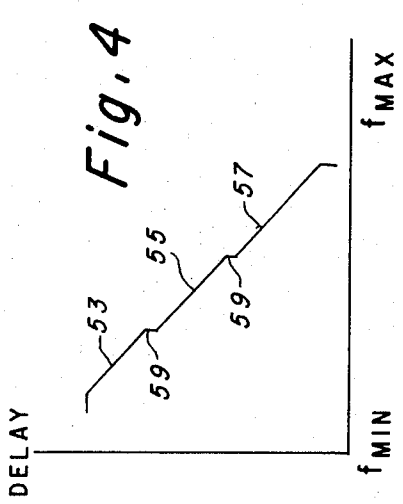


Fig. 4

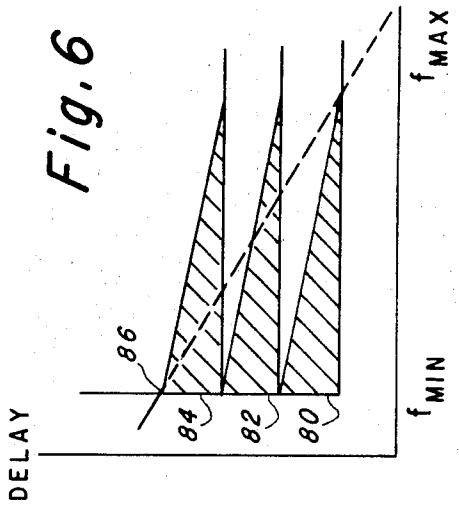


Fig. 6

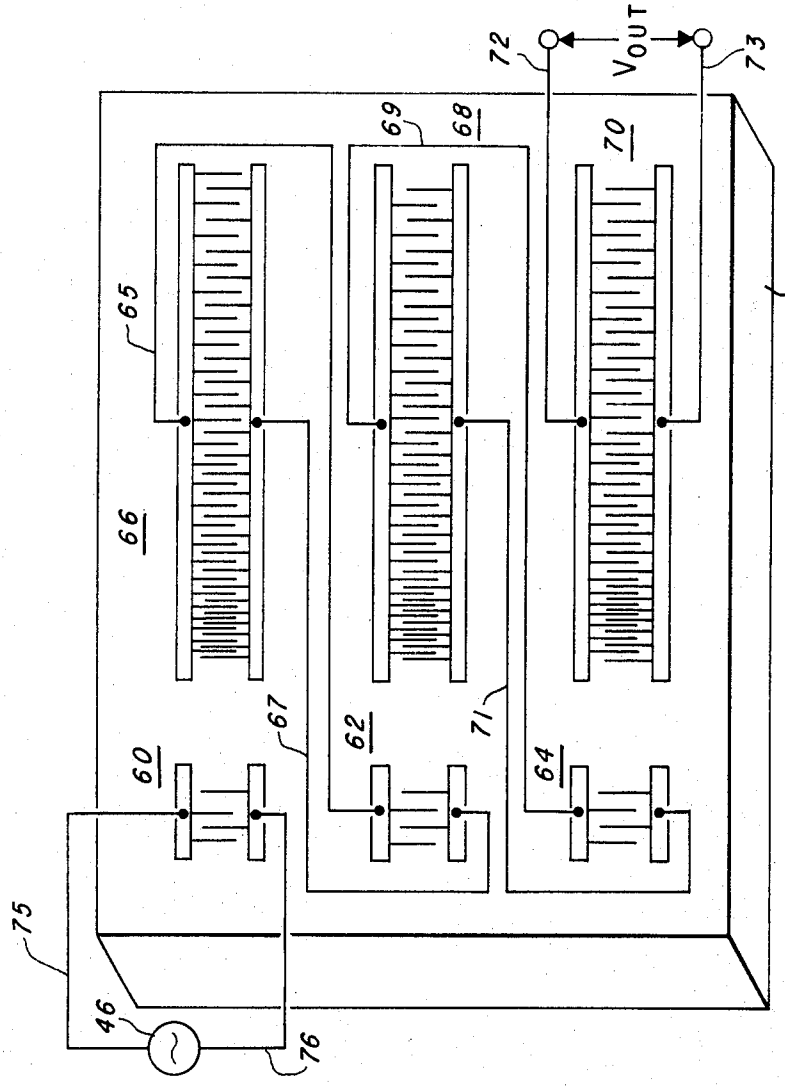


Fig. 5

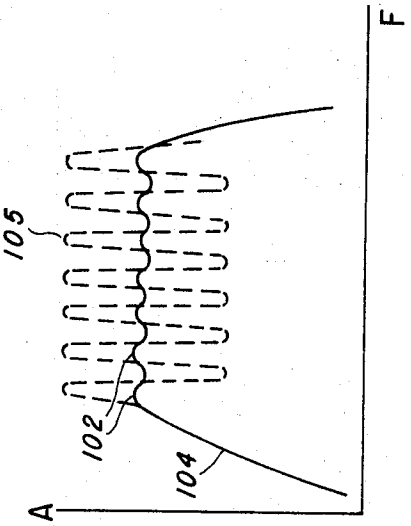


Fig. 8

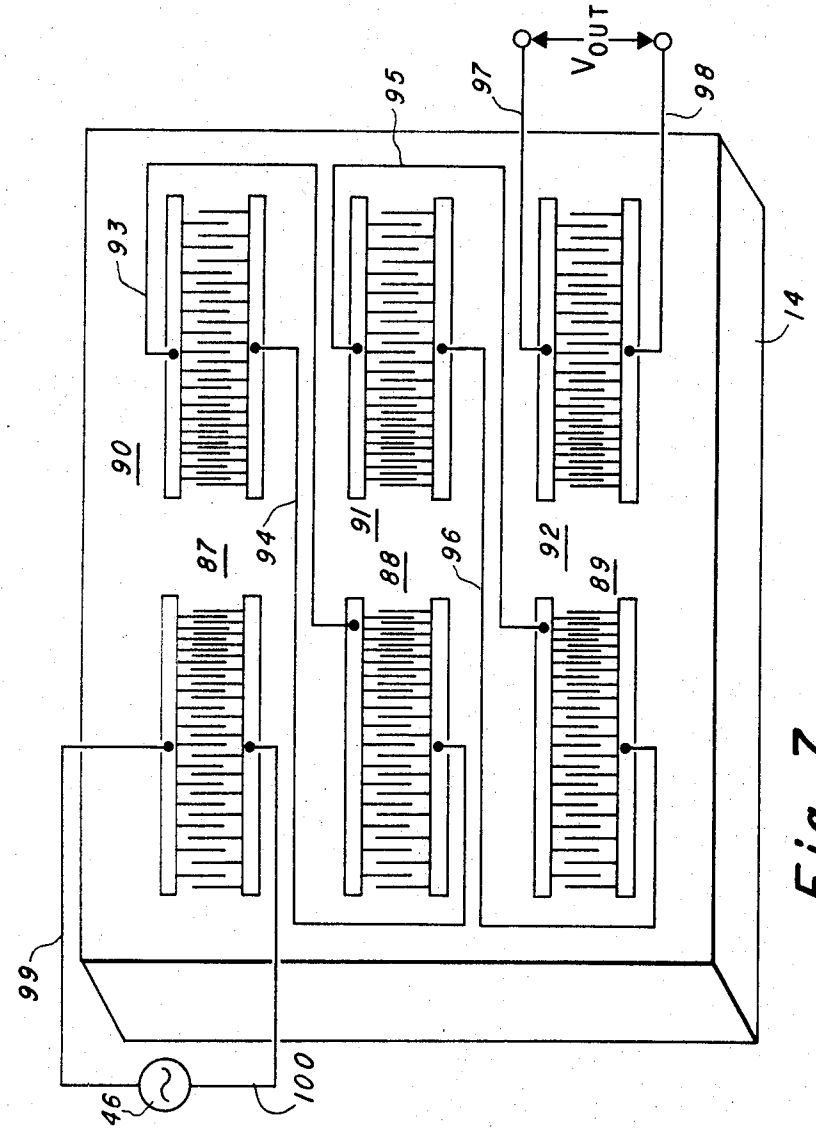


Fig. 7

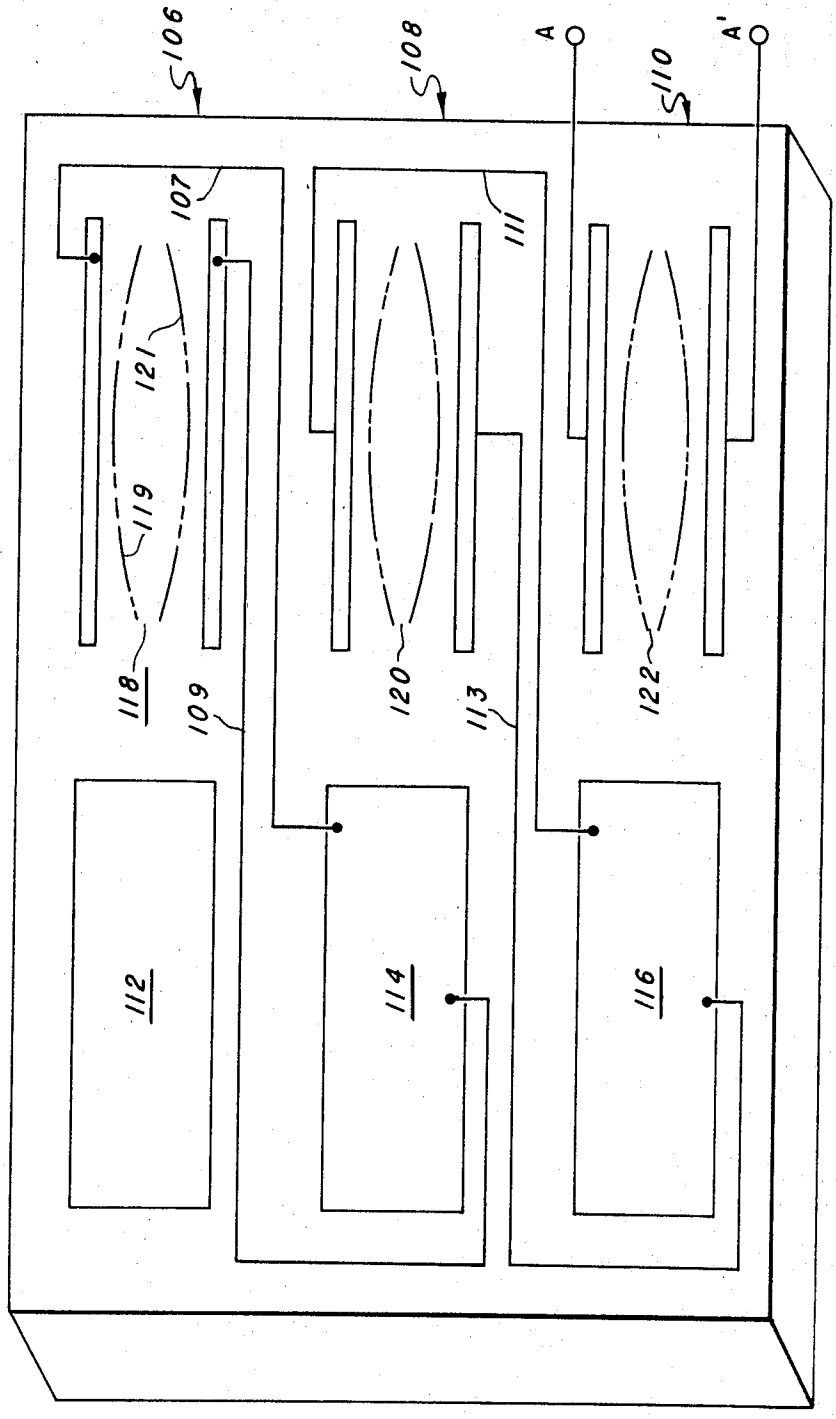


Fig. 9

CASCADED F. M. CORRELATORS FOR LONG PULSES

This invention relates to surface wave delay devices, and more specifically to surface wave frequency dispersive sections and methods for cascading same to produce a preselected delay vs. frequency characteristic.

There are many purposes, for example, in certain radar systems, in which it is required to convert a relatively long pulse or train of pulses which sweep in frequency in a predetermined manner, for example, linearly, between two limiting values of frequency, into a shorter pulse containing most of the incident energy. There are various known ways of satisfying such a requirement, such as using a dispersive electrical delay line composed of lumped circuit elements. Such electrical delay lines, however, are expensive, difficult to design and due to inevitable losses in the coils in the lumped circuits do not operate satisfactorily. Further, as a result of the large number of reactive elements employed in such lines, it is difficult to avoid the generation of false pulses due to periodic error in the line. Additionally, bulk grating dispersive delay lines, meandering lines, etc., have been used to achieve the required pulse compression. Such systems, however, have extremely high insertion loss, are unduly large, are very expensive and are sensitive to temperature variations.

It has also been proposed to use surface wave devices to produce frequency dispersive correlators. To date, however, it has not been possible to achieve large time bandwidth products with surface wave correlators because such devices have conventionally required a substrate of single-crystal piezoelectric material of a continuous length sufficient to delay the signal an amount equal to the duration of the original pulse which it is desired to compress. This large pulse length required for large time bandwidth products has required long sections of single-crystal material. Piezoelectric crystalline materials, such as lithium niobate, are very fragile and long lengths are exceedingly difficult to handle, making it impractical to use lengths of crystals greater than about three to four inches in length, which would correspond roughly to about a 20 to 30 microsecond delay. It is desirable, however, to use surface wave frequency dispersive correlators because of the advantages obtained relative to size, cost, lower insertion loss, etc.

Accordingly, it is an object of the present invention to produce a surface wave frequency dispersive correlator having a large time bandwidth product.

It is another object of the present invention to produce a surface wave frequency dispersive correlator for long pulses by cascading a plurality of relatively short delay sections.

Briefly and in accordance with the present invention, a frequency dispersive device for large time bandwidth products is produced by cascading a plurality of frequency dispersive sections, each of which comprises a plurality of surface wave interdigitated transducer arrays, at least one of which is frequency dispersive, deposited colinearly on a piezoelectric substrate. Each section contributes a portion of the total desired delay such that when all of the sections are cascaded together, a total delay equal to the pulse duration of the incident pulse is produced. In one embodiment the frequency span of the input pulse, which sweeps from a preselected low frequency to a preselected high frequency, or vice versa, is divided into a plurality of frequency segments, each segment covering a different region of the bandwidth from the low frequency point of the input pulse to the high frequency point of the input pulse. Each individual section, then, is designed to match respective frequency segments of the input pulse. In a different embodiment of the invention, each dispersive array covers the entire bandwidth of the input pulse and contributes a portion of the total delay desired. In the preferred embodiment of the invention, a Fourier transform computer program is utilized to define the optimum weighting pattern of one or both of the transducers of each of the sections to optimize the output characteristics of the overall correlator.

The novel features believed to be characteristic of this invention are set forth in the appended claims. The invention itself, however, as well as other objects and advantages thereof may best be understood by reference to the following detailed description of illustrative embodiments when read in conjunction with the accompanying drawings in which:

FIG. 1 pictorially depicts apparatus in accordance with one embodiment of the present invention wherein a plurality of sections have been cascaded;

FIG. 2 graphically depicts a typical pulse to be compressed in accordance with the methods and apparatus of the present invention;

FIG. 3 graphically depicts the pulse of FIG. 2 compressed in accordance with the present invention;

FIG. 4 depicts a graph of the delay vs. frequency characteristics of the embodiment of FIG. 1;

FIG. 5 pictorially depicts a different embodiment of the present invention;

FIG. 6 depicts a graph of the delay vs. frequency of the embodiment of FIG. 5;

FIG. 7 pictorially depicts a modification of the device of FIG. 5;

FIG. 8 is a graph of amplitude vs. frequency, depicting the Fresnel ripples produced by one section and by a plurality of identical cascaded sections; and

FIG. 9 pictorially depicts an embodiment of the present invention wherein one of the transducers of each cascaded section is amplitude weighted.

With reference to the drawings, a plurality of frequency dispersive sections, each individually effecting a relatively short frequency dispersive delay, are cascaded to produce a delay device with a large time bandwidth product. The invention may better be understood by reference to FIG. 1 wherein one illustrative embodiment is depicted.

With reference to FIG. 1, a single crystalline piezoelectric substrate is indicated at **14**. The substrate may comprise, for example, convenient lengths of lithium niobate, quartz, zinc oxide, cadmium sulfide, or other piezoelectric materials known to those skilled in the art. A plurality of frequency dispersive sections **10**, **11** and **12** are defined on the surface of the substrate **14** to define thereon separate, essentially parallel acoustic channels or sections. Each of sections **10**, **11** and **12** comprises an input transducer **15**, **19** and **23**, respectively, a frequency dispersive array **16**, **20** and **24**, respectively, and an output transducer **17**, **21** and **25** respectively. Input transducers **15**, **19** and **23**, and output transducers **17**, **21** and **25** are preferably identical broadband surface wave interdigital transducers, each defined by an interdigitated array of electrodes deposited on the surface of substrate **14**. The bandwidth of these transducers is chosen such that they pass the entire bandwidth of the input pulse without significant distortion. A first plurality of electrodes **26** are commonly connected to a conductive bar **27**. Adjacent electrodes **26** are spaced apart by one wavelength of the center frequency of the input pulse. A second plurality of electrodes **28** are commonly connected to a second conductive bar **29**, the second plurality of electrodes **28** being interlaced with the first plurality of electrodes **26** to form an interdigitated pattern. Adjacent electrodes **26** and **28** are spaced apart by one half of a wavelength of the center frequency of the input pulse. The electrodes **26** and **28** may comprise aluminum, gold, or other appropriate metals and may be formed on the substrate **14** by conventional masking and etching metallization techniques, or other techniques of defining a metal pattern on a surface. Conventionally, a layer of metal is formed on the surface of the substrate **14**. A photoresist layer is formed to overlie the metal layer, and selected areas of the photoresist layer are exposed through a mask. This mask may be formed by techniques known in the art. As described hereinafter, the mask may be designed using a Fourier transform to define the desired electrode pattern. The metal underlying the exposed areas is selectively etched using etchants known in the art to thereby form the required electrode pattern.

As an example of a train of signals that may be utilized as the input pulse, reference is made to FIG. 2 wherein a typical

pulse is depicted at **30**. Pulse **30**, shown for illustrative purposes only as being of 50 microseconds duration, may be used, for example, in a radar system wherein it is desirable that the pulse be for as great a duration as possible. Typical pulse lengths desired are from 30 to 100 microseconds. As understood by those skilled in the art, a long pulse is required in order to increase the range of radar systems, but some means for compressing the pulse to, for example, 0.2 microseconds duration, are required to obtain the necessary resolution. Such a pulse is depicted at **32** in FIG. **3**. In order to obtain pulse compression, it is necessary to code the pulse **30** in some manner. One method for coding the pulse is to very accurately sweep the pulse through a range of frequencies from a minimum frequency to a maximum frequency. For example, in FIG. **2** the minimum frequency of the incident pulse is shown as being 8997.5 megacycles and the maximum frequency 9002.5 megacycles, defining a bandwidth of 5 megacycles. It is to be understood, of course, that the frequency bandwidth, the center frequency, pulse duration, etc., will vary from system to system, depending upon the design and specification requirements.

As mentioned previously, the incident pulse **30** in the example given is in effect coded by having the pulse begin at a certain minimum frequency and end at a certain maximum frequency. In general, the pulse is swept from the minimum to the maximum frequency in a linear manner during the duration of the pulse, but this is not a restriction, and non-linear F.M. coding may also be used. Thus, when the pulse **30** depicted in FIG. **2** initially begins, only the low frequency components are transmitted. As the pulse is defined, the frequency will increase until, at the end of the pulse, only the high frequency components are transmitted. This pulse may be detected and compressed by a correlator which is precisely matched to the pulse phase and amplitude characteristics. For example, the dispersive arrays **16**, **20** and **24** shown in FIG. **1** are designed to detect a pulse having a preselected phase and amplitude. As described in more detail hereinafter, when a signal having the exact frequency variations of the incident pulse is precisely matched to the correlator, a short pulse of relatively large amplitude will be produced across the correlator output terminals.

Again, with reference to FIG. **1**, each of the dispersive arrays **16**, **20** and **24** is respectively comprised of a first plurality of electrodes designated generally at **18**, commonly connected to a first conductive bar **31** and a second plurality of electrodes **22** commonly connected to a second conductive bar **33**. Electrodes **18** and **22** are defined on the surface of the substrate in an interdigitated array using conventional masking and etching metallization techniques. The spacing between adjacent electrodes of the dispersive arrays, that is, the periodicity of the electrodes, varies in a predetermined manner from one end of the array to the other. For example, with respect to array **16**, the electrodes at the end facing the input transducer **15** are defined so that the space between the electrodes corresponds to one half the wavelength of the high frequency components of the input pulse. That is, if the input pulse **30** has a high frequency limit of 9002.5 megacycles, as shown in FIG. **2**, the spacing between adjacent electrodes **36** and **37** would correspond to one half of a wavelength of that frequency. Progressing along the dispersive array **16** in a direction away from the input transducer **15**, the spacing of electrodes varies to match the frequency variations defined by the input pulse; e.g., starting at the high frequency limit thereof and decreasing toward the low frequency limit.

For the embodiment depicted in FIG. **1**, the correlator has been divided into three separate sections respectively including dispersive arrays **16**, **20** and **24**. Each dispersive array is responsive to a different span of frequency variations of the input pulse. In other words, the frequency span of the incident pulse **30** is divided into three parts, each part having a frequency span of ΔF. Dispersive array **16** is defined such that the spacing between electrodes varies in a predetermined manner to match the upper one third of the frequency span of the input pulse **30**. The end of the dispersive array **16** facing the input transducer **15** has electrodes with a periodicity matching the maximum frequency of the input pulse, the periodicity of the electrodes varying to match the wavelengths of the input pulse such that the electrodes at the end of the dispersive array facing the output transducer **17** have a periodicity matching the maximum frequency F_{max} of the input pulse minus ΔF. Similarly, dispersive array **20** has electrodes with a periodicity at the end facing input transducer **19** corresponding with $F_{max} - \Delta F$ while the electrodes at the end of dispersive array **20** facing the output transducer **21** have a periodicity corresponding to $F_{max} - 2\Delta F$. With respect to the dispersive array **24**, the end thereof facing the input transducer **23** has electrodes with a periodicity corresponding with $F_{max} - 2\Delta F$ while the opposite end thereof corresponds to the minimum frequency of the input pulse. The frequency variations defined along the length of each dispersive array exactly corresponds with the frequency variations of a respective portion of the input pulse.

While the example shown in FIG. **1** depicts the input pulse frequency span being divided into three sections, each section being matched by a frequency dispersive array, it should be appreciated that any number of sections could be utilized in accordance with the teachings of the present invention.

In operation, the correlator depicted in FIG. **1** is electrically connected such that the respective acoustic sections are cascaded in series and the dispersive arrays are electrically cascaded in parallel. The output signal from the first acoustic section is generated across output transducer **17**. Since input transducer **15** and output transducer **17** are both broadband, all of the frequency components of the input signal are preserved. Only a small portion of the energy of the surface wave is extracted by the dispersive array **16** between F_{max} and $F_{max} - \Delta F$ since the periodicity of the electrodes of dispersive array **16** is not matched to those frequencies. The signal from output transducer **17** is electrically connected to the input transducer of the second acoustic section **19** by leads **40** and **41**. Similarly, the signal from the second acoustic section generated across output transducer **21** is electrically connected to the input transducer **27** of the third acoustic section by leads **42** and **43**. Dispersive arrays **16**, **20** and **24** are electrically connected in parallel by leads **44**–**44'**–**44''** and **45**–**45'**–**45''**. The overall electrical output terminals A–A' of the correlator are connected across the parallel combination of dispersive arrays **16**, **20** and **24**.

An input source **46** generates a pulse **30** which is applied to the input transducer **15** by leads **47** and **48**. Input transducer **15** generates an acoustic surface wave in the surface of substrate **14** in accordance with techniques understood to those skilled in the art. The frequency of the acoustic wave so generated corresponds to the input signal **30**. The low frequency components of the input signal **30** are the frequency components first generated by the transducer **15** since they are the components first received, assuming that the input signal sweeps from the low frequency to the high frequency. If, instead, the input sweeps from the high frequency to the low frequency, the signal would be applied across transducer **25** rather than transducer **15**. It should be noted that either bidirectional or unidirectional transducers may be utilized for the input and output transducers.

The low frequency components of the signal propagate along the surface of the substrate **14** and pass under the dispersive array **16**. When the low frequency components of the input signal **30** have reached the end of the dispersive array **16**, the lower one third of the frequency span of the input signal **30** will underlie the dispersive array **16**. The periodicity of the electrodes of the dispersive array **16**, however, does not correspond with the wavelengths of any of the frequency components of the lower one third of the frequency span of the input signal, and therefore the signal is very low in amplitude, consisting of the leading sidelobes of the compressed pulse generated across the output A–A' corresponding to the correlator parameters and weighting used. This portion of the output across A–A' is shown in FIG. **3** at **50**.

As the input signal continues to propagate along the surface of the substrate **14**, it is detected by the output transducer **17** and converted into an electrical signal. This electrical signal is coupled to input transducer **19** by leads **40, 41**. The input transducer **19** generates an acoustic surface wave in the second acoustic section of the substrate **14**. Again considering the low frequency components of the input signal **30**, these components travel under the dispersive array **20**. Since the periodicity of the electrodes in the array **20** does not precisely correspond with the wavelengths of any of the low frequency components of the input signal **30**, the output across A–A′ consists only of low amplitude sidelobes. Similarly, output transducer **21** detects the acoustic wave and generates an electrical output which is coupled electrically by leads **42** and **43** to input transducer **23** in the third acoustic section. Input transducer **23** generates an acoustic surface wave in the piezoelectric substrate which propagates under dispersive array **24**. At the instant that the low frequency components of the incident pulse **30** exactly underlie electrodes **49–51**, an output is generated across A–A′ since the electrodes **49-51** have been defined to exactly correspond to the wavelength of the low frequency components of the incident pulse. Similarly, at the instant the low frequency components of the incident pulse exactly underlie electrodes **49–51**, the high frequency components of the incident pulse exactly underlie electrodes **36** and **37** of dispersive array **16**. These electrodes have a periodicity exactly corresponding to the high frequency components of the input signal and therefore generate an output across A–A′. In addition, all of the frequency components of the input signal intermediate the high frequency portions which underlie electrodes **36** and **37**, and the low frequency components which underlie electrodes **49** and **51** underlie adjacent electrodes of the dispersive arrays **16, 20** and **24** which exactly correspond to the wavelength of the respective frequencies. Thus, a large pulse such as shown at **32** in FIG. **3** is produced across output A–A′. This pulse is of very short duration since the acoustic wave propagates continuously along the surface of the substrate **14** and exactly underlies electrodes having a matching periodicity at only one instant in time.

A graph of the delay vs. frequency of the output across A–A′ is shown in FIG. **4**. As may be seen, the low frequency components of the output are delayed more than the high frequency components since they have had to travel a substantially greater distance along the surface of the substrate **14** than have the higher frequency components. The output contributed by dispersive array **24** is shown by the portion of the curve depicted at **53** in FIG. **4**, while the output contributed by dispersive arrays **20** and **16** is shown respectively on the portions of the curve in FIG. **4** marked at **55** and **57**. It may be seen that the frequency dispersive delay characteristics of the curve in FIG. **4** resemble a stepped function, there being certain areas wherein there is a delay that is not frequency dependent, such areas being depicted at **59**. These undesirable non frequency dispersive delays are caused by the presence of the acoustic non-interaction spaces B of FIG. **1** wherein the acoustic wave travels along the substrate **14** without interaction with a dispersive array and thus an equal delay is imparted to all frequency components of the incident pulse **30**. These spaces within the correlator cause certain portions of the input pulse to be lost, unless the input pulse is generated in three portions (for the situation where three segments are cascaded) to exactly match the three dispersive arrays including the non-dispersive delays; that is, to exactly match the time delay vs. frequency characteristic shown in FIG. **4**.

With reference to FIG. **5**, there is depicted a modification of the circuit of FIG. **1** wherein the non-acoustic interaction areas are eliminated. As in FIG. **1**, for clarity of description, only three acoustic sections are depicted. It is to be understood, of course, that the number of acoustic sections will be determined by design consideration considering the substrate material, the total delay required, etc.

In FIG. **5**, input transducers are indicated at **60, 62** and **64**. These transducers may be identical broadband interdigital transducers having a uniform periodicity corresponding to the center frequency of the input signal that the correlator is designed to compress. Again, the input transducer must have sufficient bandwidth to encompass the bandwidth of the input pulse. Frequency dispersive arrays are indicated generally at **66, 68** and **70**. These dispersive arrays may be identical interdigitated arrays of electrodes defined on the surface of the substrate **14** in such a manner that the overall time delay vs. frequency of the correlator operates to compress the input signal as desired. For example, the electrodes may be defined on the substrate to have a graded periodicity exactly corresponding to a mirror image of the input signal. It is to be appreciated of courSe that other electrode patterns may be utilized in accordance with the present invention.

Dispersive arrays **66, 68** and **70**, and input transducers **60, 62** and **64** may be comprised of aluminum, gold, or other acceptable metals, and may be defined on the surface of the substrate **14** by conventional metallization techniques.

In operation, the output across dispersive array **66** is electrically connected to the input transducer **62** by leads **65, 67**; dispersive array **68** is electrically connected to the input transducer **64** by leads **69, 71**; and the output is obtained across dispersive array **70** by leads **72, 73**. It is to be noted that each of the disperSive arrays **66, 68** and **70** has electrodes with a periodicity matched to the entire frequency span of the input signal.

A signal source **46** generates a linear F.M. coded input signal which is applied to the input transducer **60** by leads **75, 76**. The input transducer **60** generates an acoustic surface wave which propagates along the surface of substrate **14**. As the frequency components of the input signal propagate to points underlying electrodes having a periodicity that corresponds to that frequency, a signal is generated across the dispersive array **66**. This signal is electrically coupled to the input transducer **62** by leads **65** and **67**. The input transducer **62** in turn generates an acoustic surface wave in the surface of substrate **14** which propagates along the surface of substrate **14** underlying dispersive array **68**. Similarly, an electrical signal is generated across dispersive array **68** and this signal is electrically connected to input transducer **64** by leads **69, 71**. Input transducer **64** generates an acoustic surface wave which propagates along the surface of the substrate **14** under the dispersive array **70**. Each dispersive array **66, 68** and **70** contributes a frequency dispersive delay to the input signal, the total delay corresponding to the summation of the individual delays of the respective sections. With reference to FIG. **6**, there is a plot of the delay vs. frequency of the arrangement shown in FIG. **5**. Cross-hatched areas **80, 82** and **84** pictorially depict, respectively, the delays contributed by dispersive arrays **66, 68** and **70**. The total delay is obtained by adding the individual delays of the respective sections. This is shown by the dashed line **86**. As may be seen, the total delay is extremely linear and does not exhibit the stepped response caused by acoustic non-interaction areas as shown in FIG. **4**.

While the individual dispersive arrays have been shown to be formed in separate acoustic channels on the same substrate, it is to be understood that they could be formed on separate substrates or even on opposite sides of the same substrate, as may be desired.

FIG. **7** depicts a modification of a circuit shown in FIG. **5**. In FIG. **7** input transducers are indicated generally at **87, 88** and **89**, respectively defining separate acoustic channels. These transducers may be identical interdigitated arrays of electrodes defined on the surface of the substrate **14** to effect an overall time delay vs. frequency response of the correlator operable to compress the input signal as required. In one embodiment, for example, the electrodes may be defined to have a periodicity exactly corresponding to the frequency span of the input pulse. Output transducers **90, 91** and **92** may also be identical and may, for example, correspond to a mirror image of the input transducers **87, 88** and **89**. It may be required, however, to form the output transducers to have electrodes with a periodicity different from the periodicity of electrodes

of the corresponding input transducer in order to obtain the desired correlator characteristics. Each pair of input and output transducers such as **87**, **90** operates to form a frequency dispersive section of the correlator, each section having electrodes with a periodicity corresponding to the entire bandwidth of the input signal.

In operation, a linear F.M. coded input signal is generated by source **46** and is applied to the input transducer **87** of the first acoustic channel by leads **99** and **100**. The input transducer **87** generates an acoustic surface wave in the substrate **14**, the low frequency components being generated at the lefthand side of the input transducer **87** where the electrode spacing corresponds to the low frequency components of the input signal, and the high frequency components being generated by the electrodes at the righthand side of input transducer **87**, where the electrode spacing corresponds to the high frequency wavelengths. A signal is generated across the output transducer **90** when the surface wave has propagated to a point underlying electrodes of transducer **90** having the appropriate periodicity. The high frequency components of the input signal need travel only a short distance along the surface of the substrate before being detected by electrodes at the lefthand side of the output transducer **90**, wherein the electrode spacing corresponds to the high frequency wavelength of the input signal, while the low frequency components of the generated acoustic wave must travel along the surface of the substrate the combined length of the input transducer and the output transducer before being detected by the electrodes at the righthand side of the output transducer **90**. In this manner, a frequency dispersive delay is imparted to the input signal. The electrical output generated across the output transducer **90** is connected in series to the input transducer **88** of the second acoustic channel by the leads **93** and **94**. A further delay is imparted by the second acoustic channel and the output from transducer **91** is electrically connected to the input transducer **89** of the third acoustic channel by leads **95** and **96**. The output from the device is obtained from across the last serially cascaded transducer **92**. Thus, each section imparts a discrete frequency dispersive delay across the bandwidth of the input signal producing a delay vs. frequency curve similar to that shown in FIG. **6**. The advantage of this method is the wide bandwidth obtained by using graded input and output transducers without the disadvantages of using a broadband input/output transducer which generally exhibits a very high input impedance.

In certain applications it may be desired to cascade more than about two or three frequency dispersive sections to obtain an extremely large pulse time duration capability. Certain difficulties, however, are encountered when sections are cascaded. These difficulties are caused by the fact that the frequency response (that is, amplitude and phase vs. frequency) of a frequency dispersive array inherently contains Fresnel ripples since each dispersive array has a finite time duration. These ripples are depicted at **102** in the output response **104** shown in FIG. **8**. Theoretically for a perfect correlator the number of Fresnel ripples increases as a larger time bandwidth product is obtained. When identical sections are cascaded, however, the number of Fresnel ripples does not increase but rather remains the same and the Fresnel ripples produced by each section add in amplitude, as shown in FIG. **8** by the dotted curve **105**. Even if only one frequency dispersive section is used, such as the section comprised of arrays **87** and **90** of FIG. **7**, incorrect correlation results making it unfeasible to obtain accurate sidelobes, etc., in the compressed pulse.

To overcome this incorrect correlation and deleterious Fresnel ripple effects, a detailed design must be undertaken using sophisticated techniques such as a Fast Fourier Transform (FFT) to transform from the time domain—corresponding to the actual geometry of the device—to the frequency domain or vice versa using an inverse transform. The FFT determines the weighting of the dispersive arrays required to produce the desired frequency response.

There are several methods of implementing weighting of the individual interdigital transducers to produce the required amplitude and phase vs. frequency characteristics. Specifically it is desired to obtain very low side-lobe levels. For instance the sidelobe level of an unweighted correlator is only about 13 dB whereas **30–40** dB is often required. Such sidelobe levels may be obtained by appropriate weighting of the transducer.

Weighting can be implemented by varying the interdigital electrode width effecting approximately a 2:1 weighting ratio, or by removing selected interdigital electrodes altogether, or by amplitude weighting. By amplitude weighting is meant varying the interaction length or the amount of overlapping between adjacent electrodes of the interdigital transducers. Since the signal produced when the surface wave interacts with adjacent electrodes is proportional to the amount of interaction length or overlap of the electrodes, the amplitude vs. frequency characteristics of the output signal may be varied by amplitude weighting of the electrodes.

The method of determining the weighting pattern is critical to successful operation. The first step is to determine the required impulse response to be produced by the convolutions of the cascaded sections in order to obtain the desired frequency vs. amplitude response characteristics. This is determined from the specifications of the specific application; for example, certain radar requirements would require a certain level of sidelobes, a certain pulse bandwidth, compression ratio, etc. Knowing these requirements it is known in the art to define a suitable impulse response. Substrate material limitations and required time-bandwidth define the number of sections that must be cascaded. Consider for example that N sections are required to provide the required overall time duration capability. The overall impulse response $F(t)$ of the overall correlator comprises the summation of the delay characteristics of the individual sections. In the frequency domain, the total frequency response $G(\omega)$ of the correlator is found from $F(t)$ using the FFT. The total frequency response is obtained from the product of the frequency responses of the individual sections. That is, $G_T(\omega) = G_1(\omega) \times G_2(\omega) \times \ldots G_N(\omega)$. If it is desired to have identical sections such that $G_1(\omega) = G_2(\omega)$, etc., then the required frequency response of each section is defined as the Nth root of $G_T(\omega)$. This gives the total frequency response required for each section, each section comprising two arrays of electrodes for the embodiment of FIG. **7**, or the input and dispersive arrays for the embodiment shown in FIG. **5**. The frequency response of each section $G_s(\omega)$ is defined by $G_s(\omega) = G_o(\omega) \times G_w(\omega)$ where $G_o(\omega)$ represents the frequency response of one array of electrodes of the frequency dispersive section and where $G_w(\omega)$ represents the frequency response of the other array of electrodes. If, for instance, the array having a response $G_o(\omega)$ is unweighted, the frequency response of the weighted transducer $G_w(\omega)$ may be determined by dividing $G_s(\omega)$ by $G_o(\omega)$. The mathematical expression for an unweighted transducer is known to those skilled in the art. Alternatively, the square root of $G_s(\omega)$ may be taken to give two identical arrays for each section. Also, it may be convenient to assume some arbitrary response for one array of the section and to use the FFT to design the second array. After the frequency response of a given array has been determined (using the FFT), the inverse Fourier transform is accomplished by a Fourier transform computer program to define the impulse response required for that array of electrodes. As known to those skilled in the art, the impulse response in the time domain defines the physical weighting pattern of the transducer. Using the weighting pattern so produced, a mask may be formed and the weighted transducer formed by conventional metallization techniques.

In the embodiment shown in FIG. **1**, it is not necessary to carry out the design technique above described as the overall correlator geometry is simply divided into N sections, each section covering successive spans of the frequency spread of $F_{max} - F_{min}/N$.

As understood by those skilled in the art, the required weighting of the frequency dispersive sections may not conform precisely to the conventional convolution predicted by the FFT; i.e., with amplitude weighting two colinear arrays do not convolve in an ideal manner. This incorrect convolution may be avoided by using one unweighted array, or a more complicated model of the actual convolution, or by using electrode width weighting which convolves conventionally.

With reference to FIG. **9**, there are three frequency dispersive sections or channels depicted generally at **106**, **108** and **110**, cascaded in series wherein the transducers **112**, **114** and **116** are unweighted while the respective transducers **118**, **120** and **122** are weighted in accordance with the results of the Fourier transform as above described. Amplitude weighting of the output transducer is diagrammatically depicted by the curved lines such as **119** and **121**. These lines enclose the interaction area of the electrodes making up the output transducer. It is to be appreciated that the precise shape of curves **119** and **121** are determined from the Fourier transform as above described and will vary depending upon the specific design parameters. The input transducers for the respective sections are shown diagrammatically in block form as **112**, **114** and **116**. These transducers are defined by an interdigital array of electrodes having a graded periodicity which matches the frequency variations of the input pulse desired to be compressed.

The weighted transducers **118**, **120** and **122** are also identical, the weighting of the interdigitated electrodes being determined by the Fourier transform in order to give the desired overall phase and amplitude characteristics.

In operation, the transducer **118** is electrically connected in series to transducer **114** by leads **107** and **109**, and transducer **120** is electrically connected to transducer **116** by leads **111** and **113**. The output A–A′ is obtained across transducer **122**. Each channel is reciprocal and the input and output of the correlator may be interchanged with no change in characteristics.

Although specific embodiments of this invention may have been described herein, it will be apparent to a person skilled in the art that various modifications to the details of construction shown and described may be made without departing from the scope of this invention. Specifically, it is noted that an input signal which is itself amplitude weighted may be used with the present invention.

What is claimed is:

1. A frequency dispersive correlator having a large time-bandwidth product capability for compressing an input pulse that sweeps through a span of frequencies in a predetermined manner from a first preselected frequency to a second preselected frequency comprising:

a. a piezoelectric single crystalline substrate;

b. a plurality of pairs of broadband interdigital surface wave transducers defined on the surface of said substrate, one of said transducers serving as the input transducer and the other as an output transducer, each pair of transducers aligned to define a separate acoustic channel across the surface of said substrate, the plurality of acoustic channels so defined being essentially parallel;

c. a plurality of frequency dispersive arrays, respective ones of which are interposed intermediate the input and output transducers of each of said plurality of pairs of transducers, each of said dispersive arrays being defined by an interdigitated array of electrodes deposited on the surface of said substrate, said electrodes having a graded periodicity corresponding to the wavelengths of respective portions of the frequency span of said input pulse, the bandwidth of said pulse being divided into as many successive segments of frequency spans as there are plurality of pairs of transducers, the first of said plurality of dispersive arrays having electrodes with graded periodicity corresponding to the wavelengths of the first segment of frequency spans starting with said second preselected frequency, successive dispersive arrays having electrodes of graded periodicity to match the wavelengths of successive segments of frequency spans;

d. means for electrically connecting said plurality of acoustic channels in series; and

e. means for electrically connecting said plurality of dispersive arrays in parallel whereby an input pulse sweeping in frequency from said preselected first frequency to said preselected second frequency produces an electrical signal across said correlator that is of relatively short duration with respect to said input pulse.

2. A frequency dispersive correlator having a large time-bandwidth product capability for compressing an input pulse that sweeps through a span of frequencies in a predetermined manner from a preselected first frequency to a preselected second frequency comprising:

a. a piezoelectric single crystalline substrate;

b. a plurality of frequency dispersive sections formed along separate essentially parallel acoustic channels on said substrate, each of said plurality of dispersive sections comprising input and output interdigital surface wave transducers, the input transducer being defined by an interdigital array of electrodes of graded periodicity exactly corresponding to the wavelengths of the frequency variations of said input signal, each of said output transducers being defined by an interdigital array of electrodes of graded periodicity corresponding to the wavelengths of a time reversed image of said input pulse, said input and output transducers being formed on the substrate such that electrodes having a periodicity matching the frequency components of said second preselected frequency are adjacent said input and output transducers being amplitude weighted according to the square root of the frequency response required of each of said sections; and

c. means for cascading said plurality of frequency dispersive sections whereby each section imparts a delay to said input pulse, a total delay of the cascaded sections substantially equalling the duration of said input pulse.

3. A frequency dispersive delay device having a large time-bandwidth product capability comprising a plurality of separate frequency dispersive delay sections respectively disposed in separate acoustic channels on a common piezoelectric substrate, said sections electrically connected in series, each section respectively including a plurality of collinear interdigital surface wave transducers at least one of which is defined by interdigitated electrodes having a graded periodicity corresponding to at least a portion of a selected input pulse, wherein said at least one transducer is effective to produce a portion of the total delay of said device.

4. A frequency dispersive correlator having a large time-bandwidth product capability for compressing an input pulse that sweeps through a band of frequencies in a predetermined manner from a preselected first frequency to a preselected second frequency comprising:

a. a piezoelectric single crystalline substrate,

b. a plurality of separate frequency dispersive delay section respectively disposed in separate acoustic channels on said substrate and electrically connected in series, each section respectively including collinearlly a first relatively broad band transducer having electrodes of constant periodicity corresponding to the center frequency of said input pulse and a second frequency dispersive array having electrodes with a graded periodicity corresponding to the time reversed image of the frequency span of said input pulse, each of said sections providing a portion of the total frequency dispersive delay of said correlator.

5. A frequency dispersive correlator having a large time-bandwidth product capability for compressing an input pulse that sweeps through a span of frequencies in a predetermined manner from a first preselected frequency to a second preselected frequency comprising:

a. a piezoelectric single crystalline substrate,

b. a plurality of separate frequency dispersive delay sections respectively disposed in separate acoustic channels on said substrate and electrically connected in series, each section respectively including collinearlly a first relatively broad band transducer having electrodes of constant periodicity corresponding to the center frequency of said input pulse and a second frequency dispersive array having electrodes with a graded periodicity corresponding to the time reversed image of the frequency span of said input pulse, each of said sections providing a portion of the total frequency dispersive delay of said correlator.

6. A frequency dispersive correlator having a large time-bandwidth product capability for compressing an input pulse that sweeps through a span of frequencies in a predetermined manner from a first preselected frequency to a second preselected frequency comprising:

a. a piezoelectric single crystalline substrate,

b. a plurality of separate frequency dispersive delay sections respectively disposed in separate acoustic channels on said substrate and electrically connected in series, each section respectively including collinearlly first and second interdigitated surface wave transducers, at least one of said transducers being defined by electrodes having a graded periodicity and wherein the interaction length of respective electrode pairs of said at least one transducer is selectively defined to provide amplitude weighting thereby to enhance the characteristics of said correlator, each of said sections providing a portion of the total frequency dispersive delay of said correlator.

7. A frequency dispersive correlator as set forth in claim 6 wherein said first transducer is a broad-band transducer defined by interdigitated electrodes having a constant periodicity corresponding to the center frequency of said input pulse.

8. A frequency dispersive correlator as set forth in claim 6 wherein said first transducer is defined by electrodes having a graded periodicity corresponding to the frequency span of said input pulse.

9. A frequency dispersive correlator as set forth in claim 6 wherein said second transducer has a periodicity and amplitude weighting which is defined by the inverse Fourier Transform of the desired frequency response.

* * * * *

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,675,163 Dated July 4, 1972

Inventor(s) Clinton S. Hartmann and William S. Jones

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

On the first page (Cover Sheet) left hand column after the listing of Inventors insert·

[73] Assignee: Texas Instruments Incorporated, Dallas, Texas

Signed and sealed this 20th day of February 1973.

(SEAL)
Attest:

EDWARD M.FLETCHER,JR.
Attesting Officer

ROBERT GOTTSCHALK
Commissioner of Patents

FORM PO-1050 (10-69)

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