(54) Title: METHOD AND APPARATUS FOR TRANSDUCER EXCITATION IN MEDICAL ULTRASOUND IMAGING

(57) Abstract: A method of transducer excitation in medical ultrasound imaging. Based on a stepped approximation of Gaussian modulated cosines, the transmit waveform provides bandlimited spectrum and low level of second order harmonics while retaining the duration of the transmitting within two carrier cycles. The waveform is constructed as a linear composition of four unipolar, rectangle pulses of unity amplitude. Furthermore, the described embodiment supports digitally controlled transmit apodization and focusing.

METHOD AND APPARATUS FOR TRANSDUCER EXCITATION IN MEDICAL ULTRASOUND IMAGING

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RELATED APPLICATIONS

This patent application claims the benefit of U.S. Provisional Patent Application Serial Number 60/920,606, filed March 29, 2007 in the name of Lazar A. Shifrin, and entitled "Method and Means for Transducer Excitation in Medical Ultrasound Imaging", which is incorporated herein by reference in its entirety.

TECHNICAL FIELD

This invention relates to medical ultrasound imaging systems, and, in particular, phased array scanners operating in different scan formats and imaging modes, and characteristics of the ultrasonic transmit pulses and transmit pulse generators for such scanners.

BACKGROUND

Generally, characteristics of the transmitted pulse are linked with a particular imaging mode. For example, the duration of the pulse is adjusted depending on whether the scanner operates in B-Mode, Pulsed Wave (PW) Doppler, or Color Flow Imaging. Likewise, the center frequency of the pulse is set according to the frequency response of a transducer.

To improve the propagation characteristics of the sound wave, the interrogating pulse of many medical ultrasonic imaging systems is constituted as a carrier wave modulated by a gradually rising and gradually falling amplitude envelope. In some cases, the envelope of the pulse is Gaussian in shape. Its advantage is that an initially Gaussian pulse retains its Gaussian shape during propagation through an attenuating media such as tissue.

One more reason for shaping transmit pulses has come in conjunction with the harmonic imaging where it is particularly valuable to reduce the level of even harmonics.

Summarizing, both fundamental and sub-harmonic mode ultrasound imaging are all improved by controlling the bandwidth of the frequency spectrum of the transmitted ultrasonic pulse. This bandwidth is preferably limited to frequencies around the fundamental, and is preferably sharply reduced at specified harmonics and sub-harmonics of the fundamental.

Referring to the transmit techniques, there are two main classes of ultrasound transmitters: pulsers and so-called arbitrary waveform generators (AWG).

Arbitrary waveform generators have been advanced solution for high-end ultrasound systems (by way of example, see U.S. Patents 5,549,111, 5,970,025, 6,104,673, and

5   6,469,957). AWGs can provide instantaneous change in transmit energy between transmit pulses, apodization profiles with greater resolution, and acoustic beams with lower harmonic content. Transmit signals produced by an AWG are typically Gaussian or Hamming modulated cosines individually formed for each transducer element. In operation, AWGs use stored digital representations of shaped waveforms, comprising a digital-to-analog

10   converter and a power amplifier (see U.S. Patent No. 6,537,216) to produce an analog drive signal for the transducer. However, the current implementation of arbitrary waveform transmitters is limited because of its high manufacturing cost, power dissipation and space constraints.

A typical excitation signal produced by a pulser looks like a gated square wave of a desired

15   carrier frequency. The waveform shape or envelope is essentially fixed, and, therefore, not optimal. The only adjustable parameter of a basic pulser is the length of the gate in terms of an integer number of carrier cycles. Advanced pulsers use the pulsewidth modulation (PWM) techniques and operate as described below.

To generate the PWM transmit waveform, the modulating signal is compared with a high

20   frequency sawtooth or triangle waveform that acts as a carrier. The resulting binary signal of the comparator feeds a suitable set of power switches connected to the power supplies. Having low power dissipation, PWM (or class-D) pulsers can be effectively integrated. For the same reason, the PWM pulsers are more preferable in terms of heatsinking. These factors and the relatively low cost of such ultrasound transmit circuits are the forces behind

25   the motivation of their widespread use.

By way of example, U.S. Patent No. 6,135,963 entitled "Imaging System with Transmit Apodization Using Pulse-Width Variation" describes a method and apparatus for transmit apodization by controlling the duty cycle of the pulse.

U.S. Patents No. 5,833,614 and No. 6,432,055 discuss several types of PWM transmit

30   waveforms that can be used to approximate a carrier wave modulated by a gradually rising

and gradually falling amplitude envelope. Such PWM waveforms include various unipolar sequences having two voltage levels (+V, 0) and bipolar sequences having three voltage levels (+1V, 0, and -1V).

Ultrasound equipment with harmonic imaging capabilities transmits a signal at one
5   frequency and receives the echoes at twice that frequency. A substantial obstacle to using second harmonic imaging with PWM is minimizing transmit energy at the second harmonic frequency. One solution is based on selecting the number of cycles of a carrier frequency that are transmitted in a square wave pulse burst. A greater number of carrier cycles in the burst corresponds to a narrower signal bandwidth. However, any increase in the number of
10 carrier cycles results in a lower range resolution of the system.

Pulse inversion harmonic imaging exploits two pulse bursts with the second burst as an inverse replica of the first one. This routine cancels even order distortion products that are capable of masking a valuable harmonic information generated by tissue. However, the alternation halves the image update rate. On the contrary, operating at higher frame rates is
15 particularly important for cardiac imaging.

Yet another approach is to use a bipolar (3-state) uniform square wave pulse train, which has less energy around the second harmonic frequency than does a unipolar uniform square wave pulse train of the same length.

To suppress energy at second order harmonics further, U.S. Patent No. 5,833,614 teaches the
20 transmit waveform comprising pairs of identical pulses. The width of the pulses within each pair is modulated as a function of the envelope amplitude. These pulses are phase delayed by 90 degrees relative to each other. However, increasing the number of alteration in a waveform results in higher sampling rate and, generally, a more complex transmit beamformer. At the same time, while the second harmonic is substantially suppressed, the
25 intensity of the odd harmonics is noticeable. For instance, referring to U.S. Patent No. 5,833,614, the third harmonic level is approximately – 4 dB.

An alternative 3-state, pulse width modulated, bipolar waveform is disclosed by U.S. Patent No. 6,432,055. This pulse train is constructed by summing a first component with an inverted, time-shifted version of the first component. As shown in U.S. Patent No.
30 6,432,055, by properly selecting the time interval for the time shift of the second component,

filtering of the second harmonic can be obtained. At the same time, the filtered pulse spectrum is broadband including high-order harmonics and sub-harmonics of the fundamental, each of a considerable intensity.

5   Therefore, there is still a need for improved transmit sequences that are band-limited and suppress energy at selected harmonic frequencies, and for transmit generators that are capable of generating such sequences.

SUMMARY

By way of introduction, the present invention includes a method and an apparatus for
10   ultrasound transmit excitation.

The present invention may provide a transmit waveform that is characterized by essentially bandlimited spectrum and low level of second order harmonics.

The present invention may also provide a new ultrasound transmitter that outperforms the prior art by simplicity, versatility, lower cost, and higher power efficiency, while
15   maintaining programmability for carrier frequency, transmit beamforming and apodization profile.

In a first aspect, the transmit waveform represents a stepped approximation of Gaussian modulated cosines. The transmit waveform is constructed as a linear composition of four unipolar, rectangle pulses of a unity amplitude. By properly selecting the width of the pulses
20   and their timing relationship, the transmit waveform spectrum shape is close to a Gaussian while all even harmonics are filtered out. In amplitude terms, the transmit waveform has four voltage levels, namely, +2V, +1V, 0, -1V. The zero-mean transmit waveform spans over two carrier cycles.

In the second aspect, transmit beam formation is supported by controlling the time at which
25   the excitation is initiated.

In the third aspect, sampling is occurred at a rate 8 times the predetermined carrier frequency.

Further aspect and advantages of the invention are discussed below in conjunction with the described embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be described with respect to particular embodiments thereof referring to the following drawings:

5   Figure 1 depicts a preferred transmit waveform (mathematically described as Gaussian modulated cosines) and a stepped approximation of said waveform. In Figure 1, time is measured in units of fractions of the period, T_0, of the fundamental (or carrier) frequency F_0.

Figure 2 depicts spectrums, which are associated with the waveforms of Figure 1.

Figure 3a and Figure 3b depict two alternative embodiments of constructing of a stepped
10   approximation of the Gaussian modulated cosines of Figure 1.

Figure 4 is a block diagram illustrating a conventional ultrasonic imaging system operative to implement the present invention.

Figures 5a through 5e illustrate timing diagrams of the operation of the waveform generator.

Figure 6 is a block diagram of an embodiment of an ultrasound transmitter suitable for
15   implementation with the imaging system of Figure 4.

Figure 7 is a block diagram of another embodiment of an ultrasound transmitter suitable for implementation with the imaging system of Figure 4.

Figure 8 is a schematic diagram of an embodiment of the current driver of the ultrasound transmitter of Figure 6.

20   Figure 9 is a schematic diagram of an embodiment of the current driver of the ultrasound transmitter of Figure 7.

DETAILED DESCRIPTION

The following sections will first discuss an improved ultrasonic transmit sequence that
25   represents a stepped approximation of Gaussian modulated cosines and will then discuss different transmitters for generating such signals.

TRANSMIT WAVEFORMS

Typically, in order to generate a pulsewidth modulation (PWM) transmit sequence, the
envelope of an amplitude-modulated waveform is first sampled at a plurality of points. The
number of points sampled depends on the sampling frequency, F_S, and the duration of the
envelope, T_E. Preferably, $F_S = M \cdot T_E$, where M is the number of samples. Lowering the
value of M results in fewer pulses in the PWM transmit pulse train and, generally, a less
complex transmit beamformer. In any case, the width of each pulse is proportional to the
amplitude of the envelope at the sampling point. Thus, the duration of the pulses increases
gradually to a maximum value and then decreases gradually like the amplitude of the
envelope.

To reduce the transmitter complexity and manufacturing cost, the PWM transmit sequence is
rather coarsely sampled, such as at a rate of eight or even four samples per carrier cycle.
Thus, in order to eliminate possible aliasing effects, the signal to be sampled should be
limited in spectral content. Consequently, the original PWM transmit waveform includes at
least two carrier cycles.

Implementing a relatively short PWM transmit waveform, an ultrasound system would
provide a satisfactory range resolution. However, such a waveform has a high second
harmonic content. Thus, with the exception of using a pulse-inversion technique, a
traditionally composed PWM transmit sequence is not suitable for harmonic imaging. As
previously discussed, various filtering techniques allow suppression of the second harmonic
distortion. However, this results in a higher sampling rate, widens the transmit spectrum,
and might increase the intensity of the odd harmonics.

In the present invention, synthesis of an improved transmit pulse train involves a stepped
approximation of Gaussian modulated cosines as shown in Figure 1. Then, the step-
approximated transmit waveform of Figure 1 is decomposed into three base pulse sequences
as depicted as A, B, C and A+B+C in Figure 3a. An alternative but equivalent transmit
waveform partition is shown in Figure 3b. The base waveforms A and B in Figures 3a and
3b are unipolar in that the polarity of two or more pulses is the same (e.g., positive or
negative) regardless of the amplitude. The pulse train C comprises two unipolar unity
amplitude rectangle pulses. The polarity of C is inverted with respect to A or B. Both
partitions satisfy the following basic requirements:

The coupling between ultrasonic transmitters and transducers may be provided by a transformer, in one embodiment, or a capacitor, in another embodiment, and, thus, no DC component in the transmit waveform is expected. Referring to Figure 3a, this condition can be achieved if a voltage-time product of positive (A + B) and negative (C) pulse trains are

5   equal. With unity amplitude rectangular pulses, the voltage-time product yields:

$$\tau_1 = 2 \cdot \tau_2 - T_0/2 \tag{1}$$

where the time T_0 is the period of the fundamental frequency F_0, the time τ_1 is the duration of a pulse exhibited in the A pulse train, the time τ_2 is the duration of pulses presented in the C pulse train.

10   The spectrum, $S_0(f)$, of a unity amplitude rectangular pulse having a duration of τ is given by:

$$S_0(f) = \frac{\sin(\pi \cdot f \cdot \tau)}{\pi \cdot f} \tag{2}$$

where f is the frequency variable.

Thus, the spectrums of the base sequences A, B, and C can be expressed as:

15
$$S_A(f) = \frac{\sin(\pi \cdot f \cdot \tau_1)}{\pi \cdot f} \tag{3}$$

$$S_B(f) = \frac{\sin(\pi \cdot f \cdot T_0/2)}{\pi \cdot f} \tag{4}$$

$$S_C(f) = \frac{\sin(\pi \cdot f \cdot T_0/2)}{\pi \cdot f} - \frac{\sin[\pi \cdot f \cdot (2 \cdot \tau_2 + T_0/2)]}{\pi \cdot f} \tag{5}$$

Substituting Equation 1 in Equation 3 yields:

$$S_A(f) = \frac{\sin[\pi \cdot f \cdot (2 \cdot \tau_2 - T_0/2)]}{\pi \cdot f} \tag{6}$$

20   Summing Equations (4), (5), and (6), the frequency spectrum of the step-approximated transmit waveform, $S_\Sigma(f)$ is:

$$S_\Sigma(f) = S_A(f) + S_B(f) + S_C(f) = \frac{2\sin(\pi f\, T_0/2)}{\pi f} \cdot \left[1 - \cos(2\pi f \tau_2)\right] \quad (7)$$

In particular, the fundamental frequency peak is located at $f = F_0 = 1/T_0$. Substituting $f = F_0$ into Equation 7, the peak value yields:

$$S_\Sigma(F_0) = \frac{2T_0}{\pi} \cdot \left[1 - \cos\left(2\pi \frac{\tau_2}{T_0}\right)\right] \quad (8)$$

5 Referring to Equation 7 again, the even harmonics are even multiples of the fundamental. Thus, the even harmonics frequencies, F_{2n}, can be determined as $F_{2n} = 2nF_0 = 2n/T_0$, where $n = 1, 2, 3$, etc. Inserting $f = F_{2n}$ into the argument of the sine function of expression (7) yields $\sin(\pi f T_0/2) = \sin(\pi n) = 0$. Therefore, satisfying Formula 1, the spectrum of the transmit waveform of Figure 3a contains no even harmonics.

10 The techniques of the present invention may allow suppressing a range of frequencies adjacent to the second harmonic. To confirm this analytically, it is noted that the term in square brackets of Equation 7 is zeroed if the cosine argument is equal to $2n\pi$. This occurs at the frequencies $f = F_{ABSORPTION}(n)$ satisfying the condition $2\pi f \tau_2 = 2n\pi$. Thus, $F_{ABSORPTION}(n) = n/\tau_2$. For example, by selecting $\tau_2 = 3T_0/8 = 3/8F_0$, absorption lines of the
15 transmit spectrum are given by:

$$F_{ABSORPTION}(n) = \frac{8nF_0}{3} \quad (9)$$

As shown in Figure 2, the first absorption line is located at $F_{ABSORPTION}(1) = 8F_0/3 \approx 2.7 \cdot F_0$. Thus, the transmit sequence at the present invention may provide bandlimited spectrum and good range resolution. Furthermore, its spectrum comprises no second order harmonics of
20 the fundamental.

The method of generating an ultrasonic transmit waveform is illustrated by the graphs of Figures 5a through 5e, in which time is plotted on the X-axis and voltage on the Y-axis. Time is measured in units of fractions of the period, T_0, of the fundamental frequency F_0. A first, second, and third unipolar base waveforms of unity amplitude having the above-
25 defined temporal characteristics are respectively shown in the graphs of Figures 5a through 5c. To provide a zero-DC transmit waveform, the first base waveform is inverted as shown

in the graph of Figure 5d. Then, the inverted first, second, and third base waveforms are summed providing the proposed approximation of Gaussian modulated cosines as depicted in the graph of Figure 5e.

In an alternative embodiment, the transmit waveform can be arranged by first summing the second and third base waveforms and subsequent subtracting the first base waveform from the obtained sum.

LOW-DISTORTION ULTRASOUND TRANSMITTER

Figure 4 is a block diagram illustrating a medical ultrasonic imaging system 400. The system 400 comprises a controller 401, a multi-channel transmit and receive beamformers (402 and 408, respectively), a plurality of transmit/receive (T/R) switches 404, an array of transducers 406, and an image processor 410.

The insonification of a body structure is provided by the transmit beamformer 402 that applies respective transmit waveforms via the transmit/receive (T/R) switches 404 to the transducer array 406 in response to the controller 401. (Although the imaging system 400 is described for transmitting waveforms to and receiving waveforms from a body structure, the imaging system and the elements thereof may be used with other structures and in other systems.)

Each channel of the transmit beamformer 402 comprises a transmitter and a source of sampled waveform information representative of the desired transmit waveform. To steer and focus the transmit beam at a particular focal position, the transducers 406 are to be excited with different time delays. This is achieved by applying per-channel delay to the desired transmit waveform. Further details on beamforming can be found in foregoing section.

During receive, the transducers 406 detect echoes from body structures. The receive waveforms are applied via the transmit/receive switches 404 to a multi-channel receive beamformer 408, which applies suitable delays and filters to create a coherent sum for selected points along the spatial axis for application to an image processor 410 in response to the controller 401.

Figure 6 is a block diagram illustrating a first embodiment of a single transmit channel transmitter 600 capable of being incorporated into the beamformer 402 for providing the beamforming of the present invention. The transmitter 600 comprises a power amplifier 610, a waveform generator 620, a phase-locked loop (PLL) 630, three programmable current

5   drivers 650, and a digital-to-analog converter (DAC) 670. In one embodiment, the programmable current drivers 650 are identical. The interface of the transmitter 600 comprises a clock terminal 660, a triggering terminal 662, a reference voltage input 664, and two command ports, 666 and 668, responsive to receive beam formation data (focusing and apodization, respectively) in a digital format.

10   The power amplifier 610 may be a conventional transformer-coupled class B push-pull transistor amplifier. The transistors of the power amplifier 610 operate in a common-gate (or common-base) mode providing essentially low input impedance at their sources (or emitters). The current drivers 650 feed the power amplifier 610 via respective outputs 652. A low input impedance of the amplifier 610 enables direct summing of two currents

15   provided by those drivers 650 responsible for the second and third base waveforms (waveforms 5b and 5c, respectively,) as shown in Figure 5.

The phase locked loop 630 includes a voltage controlled oscillator (VCO) 632, a frequency divider 634 (such as a twisted ring counter) for frequency-dividing an output from the VCO 632, a phase-frequency detector 636 for comparing an output from the frequency divider 634

20   with a phase of an external reference signal applied via the clock terminal 660, a charge pump and filter 638 for controlling the oscillator frequency of the VCO 632 on the basis of an output from the phase frequency detector 636, and a multiplexer 639 for selecting a phase of the oscillator frequency. In one embodiment, the frequency divider 634 comprises a 2^{N-1}-stage (N is an even integer) twisted ring counter providing 2^N phase-shifted clock lines from

25   inverted and non-inverted outputs, which are sequentially coupled to the inputs of the multiplexer 639 in ascending order of the value of phase shift.

The waveform generator 620 includes three blocks 622, one for the base waveforms, and an address counter 626. Each of the blocks 622 stores a 4-bit length binary word (i.e., 16 in decimal) as depicted in Figure 5. (A 4-bit length binary word is for illustrative purposes.

30   Other numbers of bits may be used.) When a block 622 is read with an $8xF_0$ clock, the resulting sequence defines a waveform having $2T_0$ in duration. To generate the first, second,

and third base waveforms synchronously with a phase-shifted reference clock, the address counter 626 is fed by the multiplexer 639. The process of firing is initiated via the triggering terminal 662. The base waveforms are outputted through data ports 624 and respectively applied to the current drivers 650.

5   The DAC 670 is controlled by a digital code loaded into the port 668. Accordingly, the DAC output 654 becomes a product of a voltage applied to the reference input 664 and the digital code. Thus, the DAC 670 generates a scaled voltage in response to a code provided by the command register.

Figure 8 is a circuit diagram illustrating the ON/OFF switchable current driver 650 shown in
10   Figure 6. The current driver 650 comprises a logical inverter 802 having an open-drain output 808, a resistor 804, and a MOSFET transistor 806 having a gate, drain and source. The transistor source is coupled to the open-drain output through the resistor 804. Referring to Figure 6, the transistor gate 810 is fed by the DAC output 654. In an alternative embodiment, a bipolar transistor in a common base configuration may be used. Regardless
15   on the implementation, the current flowing through the resistor 804 in the ON state is proportional to the DAC output voltage denoted as REF in Figure 6. Signals for controlling ON-OFF states of the current driver 650 are produced by the waveform generator 620 (Figure 6) and applied to the inverter input 812.

For low levels of the DAC output, the threshold voltage tolerance of the transistor 806 may
20   degrade the accuracy of apodization. In view of that, the second embodiment shown in Figure 7 provides a modified transmitter architecture.

Figure 7 is a block diagram illustrating a second embodiment of a single transmit channel transmitter 700 capable of being incorporated into the beamformer 402 for providing the beamforming of the present invention. The transmitter 700 comprises a power amplifier
25   710, a waveform generator 720, and a PLL 730, which are identical to the respective elements 610, 620, and 630 shown in Figure 6. Similarly, the interface of the second embodiment includes a clock terminal 760, a triggering terminal 762, a reference input 764, and two command ports, 766 and 768. The difference between the above embodiments lies in the arrangement of current drivers 750.

Figure 9 depicts a circuit diagram of the current driver 750 shown in Figure 7. The programmable current driver 750 comprises a digitally programmable resistor (DPR) 904 with enable and a MOSFET transistor 906. The transistor 906 is arranged with its gate 918 coupled to the reference input 664, the source coupled to a common node 908 of the

5   programmable resistor 904, and the drain to providing the driver output 916. The programmable resistor 904 comprises a plurality of 2-input open-drain NAND gates 910 and a plurality of resistors 912. The resistors 912 are binary weighted. Each resistor 912 is coupled between the open-drain output of a gate 910 and the common node 908. A first input of each gate receives a respective bit of a binary word applied to the command port

10   668. This binary word represents a desired resistance of the programmable resistor 904.

All second inputs of each gate are coupled together exhibiting a node 914 and, thus, a logical "1" applied to the node enables conducting of the gates having a logical "1" on their first inputs. Therefore, the transistor 906 generates a current pulse whose timing is determined by the waveform generator 720. In an alternative embodiment, thermometer coding scheme

15   or its combination with binary techniques may be used. The amplitude of this pulse may be directly proportional to the reference signal and inversely proportional to the resistance.

Referring to Figure 9, programmable resistance is varied from 8R/15 to 8R. Thus, for a fixed voltage at the gate of the transistor 906, the amplitude of the produced current pulses will approach the range of 24 dB. Other dynamic ranges, including lesser or larger ranges

20   may be used. By any means, this range defines attainable amplitude resolution for apodization.

BEAMFORMING

The two most common beamforming approaches are the time delay (shift) and phase shift.

25   The time delay approach allows focusing and steering the beam by introducing per-channel time delays that are independent from the operating frequency and bandwidth. Instead of applying true time delays for each channel, the phase shift beamformer converts a required delay to an equivalent phase shift at a specified frequency. Since a phase-shift technique is adapted to form a beam at a predetermined frequency, the respective imaging systems are

30   more narrowband than those employing time-delay beamformers.

An absolute time shift may be implemented by delaying the composed waveform or delaying a start of waveform generation. To delay the composed waveform, transmit beamformers may use field programmable gate arrays (FPGA) or first-in, first-out (FIFO) buffers for each channel. Delaying a start point of waveform generation is also provided on a per-channel

5   basis but it consumes much less hardware resources.

Implementing the second method of the time shift, the absolute delay is programmed into the programmable delay counter. This counter counts a number of clock cycles associated with the absolute delay in response to a start-of-transmit signal (SOT). A transmit sequence is initiated at the end of the counting period. Thus, the accuracy of delay is defined by the

10   counter clock rate.

Those experienced in the art understand that routing a plurality of highly sampled (e.g., broadband) SOT signals might be complex. For this reason, one embodiment of the present invention is described such that the applied SOT signal is produced with a $T_0/8$ sampling interval (a 45^0 sampling in terms of phase), e.g., an ultrasound system incorporating the

15   present invention would responsible for merely coarse focusing.

To support fine focusing, the implemented PLLs 630 and 730 are configured to produce N (N is an even integer) phase-shifted clocks at the $8F_0$ rate. Thus, the phases of these clocks are evenly spaced within the 45^0 range. One of the above clocks is selected by the multiplexers 639 and 739 and used for timing the waveform generators 620 and 720.

20   Consequently, the transmit waveforms may have N discrete positions relative to the one determined by the applied "coarse" SOT (or triggering) signal. Since the adjacent discrete positions are shifted in time by $T_0/8N$, the beamformer phase resolution yields $45^0/N$ in phase. For instance, implementing an 8-stage twisted ring counter, a 2.8^0 phase accuracy can be achieved.

25   Some features of the above embodiments of the present invention can be summarized as follows:

1.   The transmit waveform may be characterized by bandlimited spectrum and low level of second order harmonics while retaining the duration of the transmitting within two carrier cycles.

2.   The ultrasound transmitters support digitally controlled transmit apodization and fine focusing.

3.   The embodiments may provide time-independent output impedance.

While the invention has been described above by reference to various embodiments, it would
5   be understood that many changes and modifications could be made without departing from the scope of the invention. For example, different waveform generators, current drivers, switches, or output amplifier configurations may be used. It is therefore intended that the foregoing detailed description be understood as an illustration of the presently preferred embodiments of the invention, and not as a definition of the invention. It is only the
10   following claims or added claims, including all equivalents, are intended to define the scope of this invention.

WHAT IS CLAIMED IS:

1.   A method of transducer excitation in medical ultrasound imaging system, the method comprising the steps of:

(a)   constructing an excitation waveform in a predetermined manner, wherein the waveform represents a gated, stepped approximation of a Gaussian envelope multiplied by a cosine carrier;

(b)   selecting the carrier frequency, F_0, in accordance with a fundamental frequency of the transducer, $F_0 = 1/T_0$.

2.   The method of claim 1 wherein the step (a) further comprises constructing the excitation waveform within an excitation interval of $2 \, T_0$.

3.   The method of claim 1 wherein the step (a) further comprises constructing the excitation waveform as a bipolar waveform.

4.   The method of claim 1 wherein the step (a) further comprises constructing the excitation waveform as a zero-DC waveform.

5.   The method of claim 1 wherein the step (a) further comprises synthesizing the excitation waveform to have no even harmonic content.

6.   The method of claim 1 wherein the step (a) further comprises:

(a)   arranging a first, second and third base waveforms, and wherein said first base waveform comprises a first and second pulses characterized by equal duration of T_1, where $T_1 = 0.375 \, T_0$.

7.   The method of claim 6 wherein said first and second pulses of said first base waveform are unipolar and characterized by a uniform amplitude.

8.   The method of claim 6 wherein the step of arranging the first base waveform further comprises:

(a)   shifting the second pulse from the first pulse in time, said shift is equal to $T_0/2$;

(b)   superimposing the center of said first base waveform over the center of the excitation interval.

9.   The method of claim 6 wherein the second and third base waveforms are unipolar, uniform amplitude pulses having duration of $T_1 = 0.375 \, T_0$; and

wherein the step of arranging the second and third base waveform further comprises the steps of:

(a)   shifting the center of the second base waveform $T_0/16$ in time from the center of the excitation interval in the backward direction;

(b)   shifting the center of the third base waveform $T_0/16$ in time from the center of the excitation interval in the forward direction.

10.   The method of claim 1 wherein the step of constructing an excitation waveform includes a step of combining said base waveforms, said combining step further comprises inverting of the polarity of the first waveform.

11.   An ultrasound transmitter for generating an excitation waveform with programmable apodization and time (phase) shift, the transmitter comprising:

a phase locked loop (PLL) generating a clock signal with user-selectable phase shift in response to a reference clock having a frequency $8xF_0$, where F_0 is a fundamental frequency of the transducer;

a waveform generator having a plurality of waveform outputs for providing respective waveforms in response to a trigger signal and the clock signal, and constructing an excitation waveform in a predetermined manner, wherein the waveform represents a gated, stepped approximation of a Gaussian envelope multiplied by a cosine carrier; selecting the carries frequency, F_0, in accordance with a fundamental frequency of the transducer;

first, second and third programmable current drivers each having a waveform input and having a current output, and providing current signals from the current output in response to a voltage reference and a respective waveform applied to a corresponding waveform input from a corresponding waveform output of the waveform generator;

a power amplifier for generating an excitation waveform in response to current signals on the current outputs of the current drivers; and

a first and second command registers controlling said apodization factor and time (phase) shift of the excitation waveform.

12.   The ultrasound transmitter of claim 11, wherein:

the waveform generator stores and reads the first, second and third base

waveforms via a first, second and third data ports, said waveform generator

comprises a 3x16 addressable matrix of binary data and a 4-bit address counter

which maintains said addressing, and wherein:

said counter further comprises timing and firing inputs, said timing and firing

inputs are respectively coupled to the multiplexer output and the triggering terminal.

13.   The ultrasound transmitter of claim 11,

wherein the power amplifier is a transformer-coupled class B push-pull

amplifier comprising first and second high-voltage transistors, each of said first and

second high-voltage transistors having a gate, source, and drain, both transistors

coupled in a common-gate configuration, and

wherein the source of the first high-voltage transistor is coupled to the current

output of the first current driver, the source of the second high-voltage transistor and

the current outputs of said second and third current drivers are coupled together.

14.   The ultrasound transmitter of claim 11,

wherein the PLL includes a voltage controlled oscillator (VCO), a frequency

divider for frequency-dividing an output from the VCO, a phase-frequency detector

for comparing an output from the frequency divider with a phase of said reference

clock, a charge pump for controlling the VCO frequency on the basis of an output

from said phase detector, and a multiplexer and

wherein said frequency divider comprises a 2^{N-1}-stage (N is an even integer)

twisted ring counter providing 2^N phase-shifted clock lines from inverted and non-

inverted outputs, which are sequentially coupled to the inputs of said multiplexer in

ascending order of the value of phase shift, said multiplexer having 2^N inputs, an

output providing said clock signal and a select port coupled to said first command

register.

15.   The ultrasound transmitter of claim 11, wherein each of said first, second and

third current drivers further comprises a low-voltage transistor, said transistor having a gate,

a source, and a drain supplying the current driver output, the gates of said low-voltage

-18-

transistors of the first, second and third current drivers being coupled together with the reference voltage source.
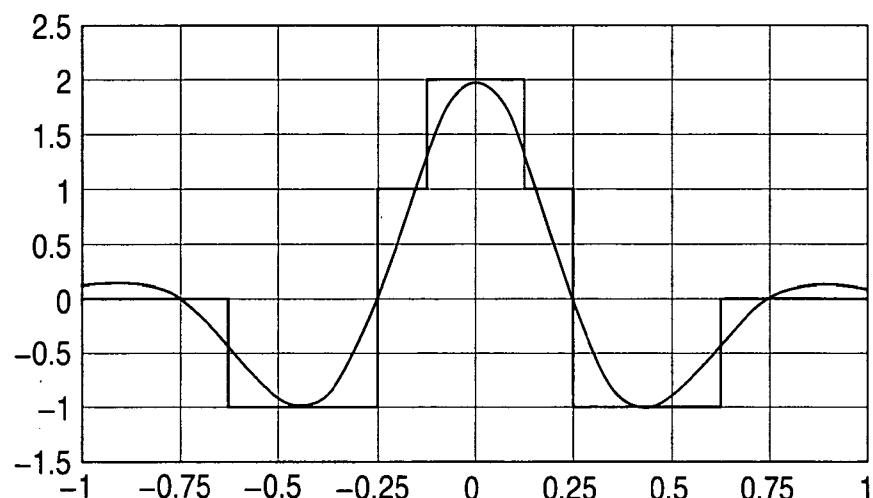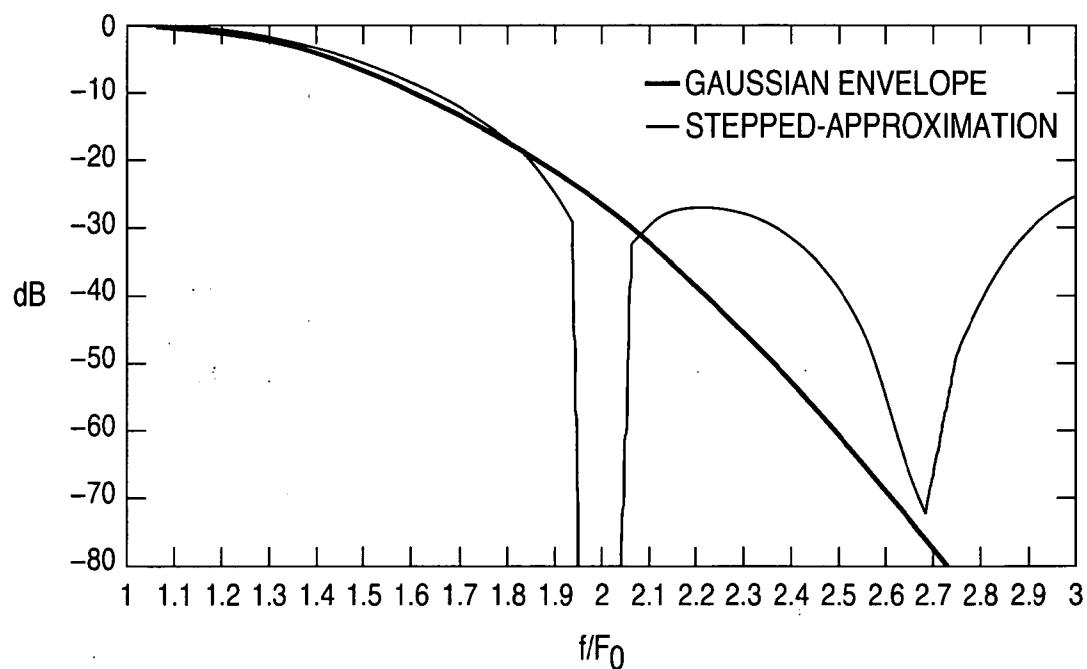
16.   The ultrasound transmitter of claim 15, wherein each of said first, second and third current drivers further comprises a logical inverter and a resistor, said logical inverter having an input node and an open-drain output, said resistor coupled between said open-drain output and the source of said low-voltage transistor, said input nodes are respectively coupled to the first, second and third data ports of said waveform generator.
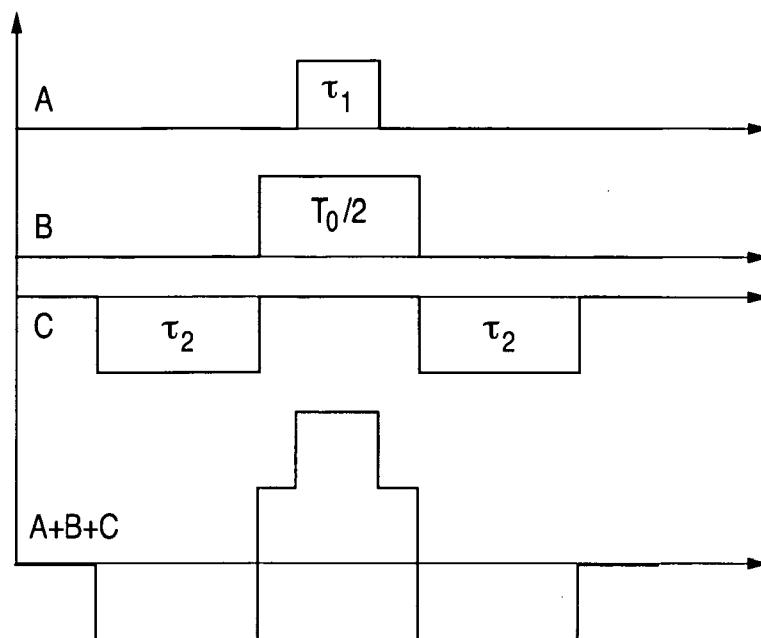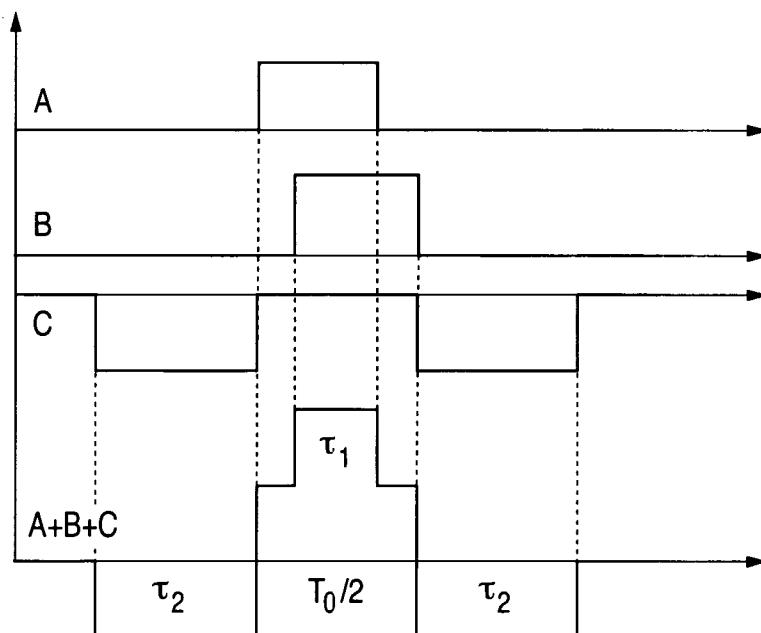
17.   The ultrasound transmitter of claim 15, wherein said reference voltage source comprises a digital-to-analog converter (DAC) arranged to generate a scaled voltage in response to a code provided by the second command register.

18.   The ultrasound transmitter of claim 15, wherein each of said first, second and third current drivers further comprises a plurality of binary weighed resistors, each having two terminals, and a plurality of NAND gates, each having two inputs and an open-drain output.

19.   The ultrasound transmitter of claim 18, wherein:
the first terminals of said resistors are respectively coupled to the open drain outputs of said NAND gates;
the second terminals of said resistors are coupled together with the source of said low-voltage transistor; and
the first inputs of said NAND gates are coupled to corresponding bit lines of the second command register.

20.   The ultrasound transmitter of claim 19, wherein the second inputs of the NAND gates of said first, second and third current drivers are respectively coupled to the first, second and third data ports of said waveform generator.

FIG. 1



FIG. 2

FIG. 3A

FIG. 3B

400

FIG. 4
(PRIOR ART)

| -1 | -3/4 | -1/2 | -1/4 | 0 | +1/4 | +1/2 | +3/4 | +1 |
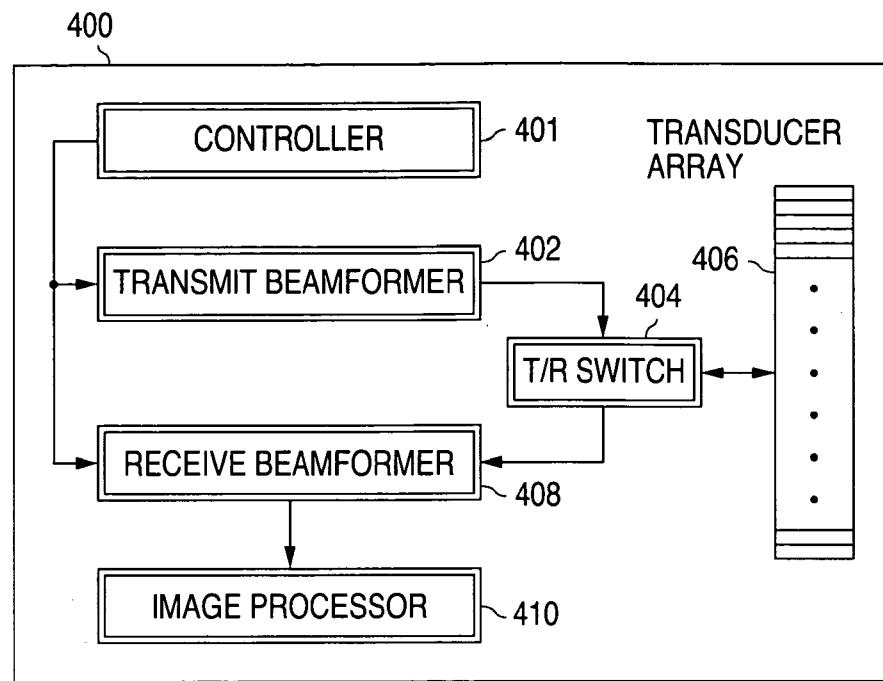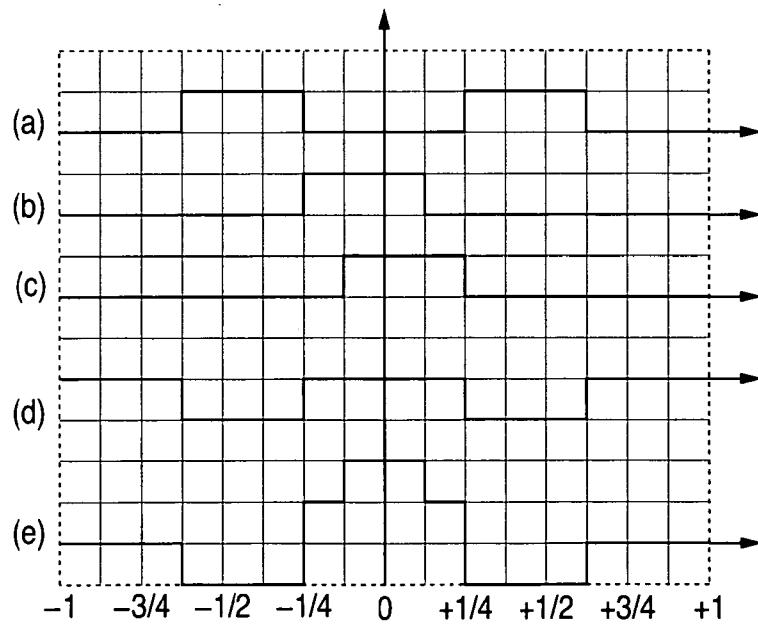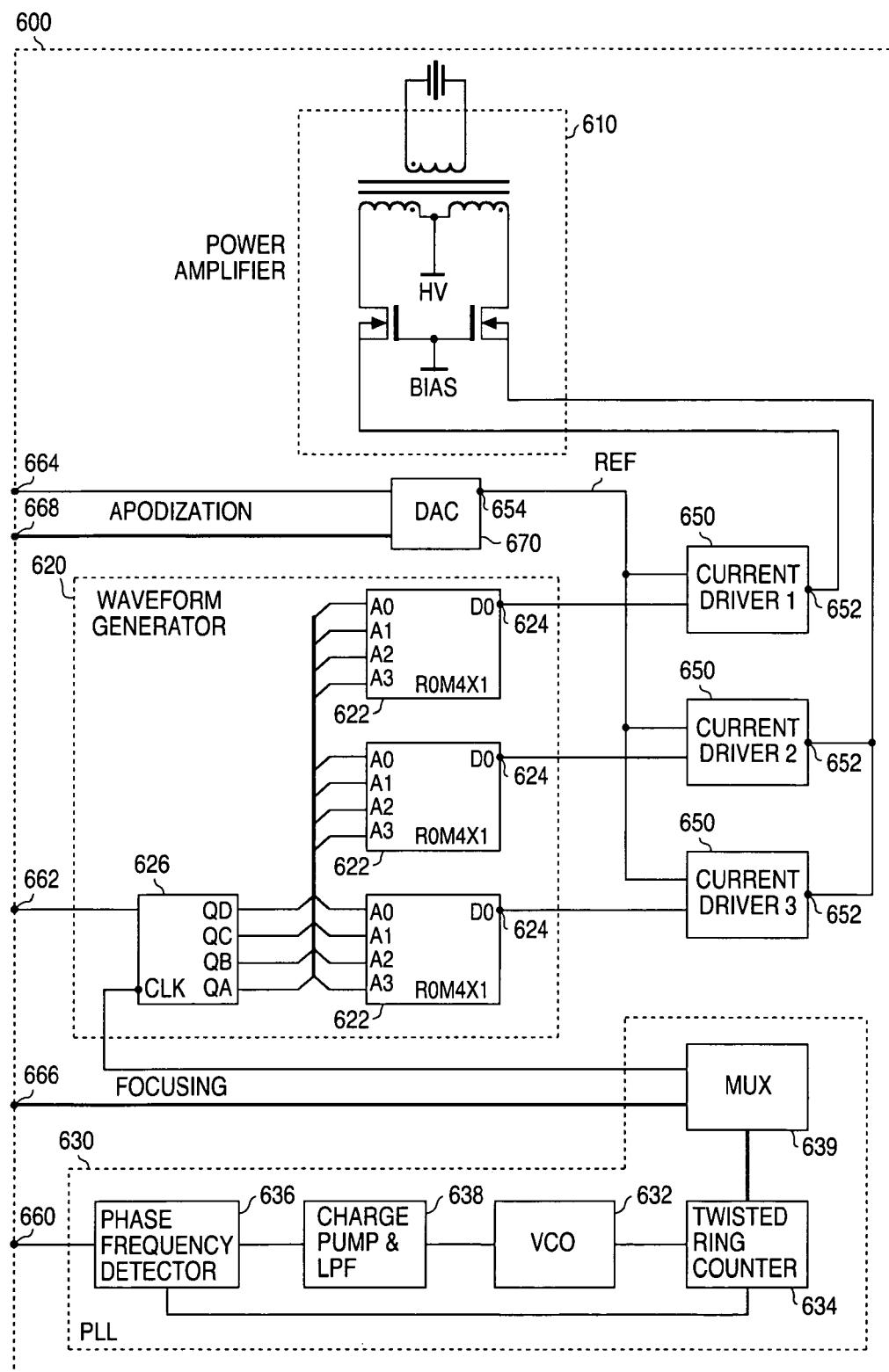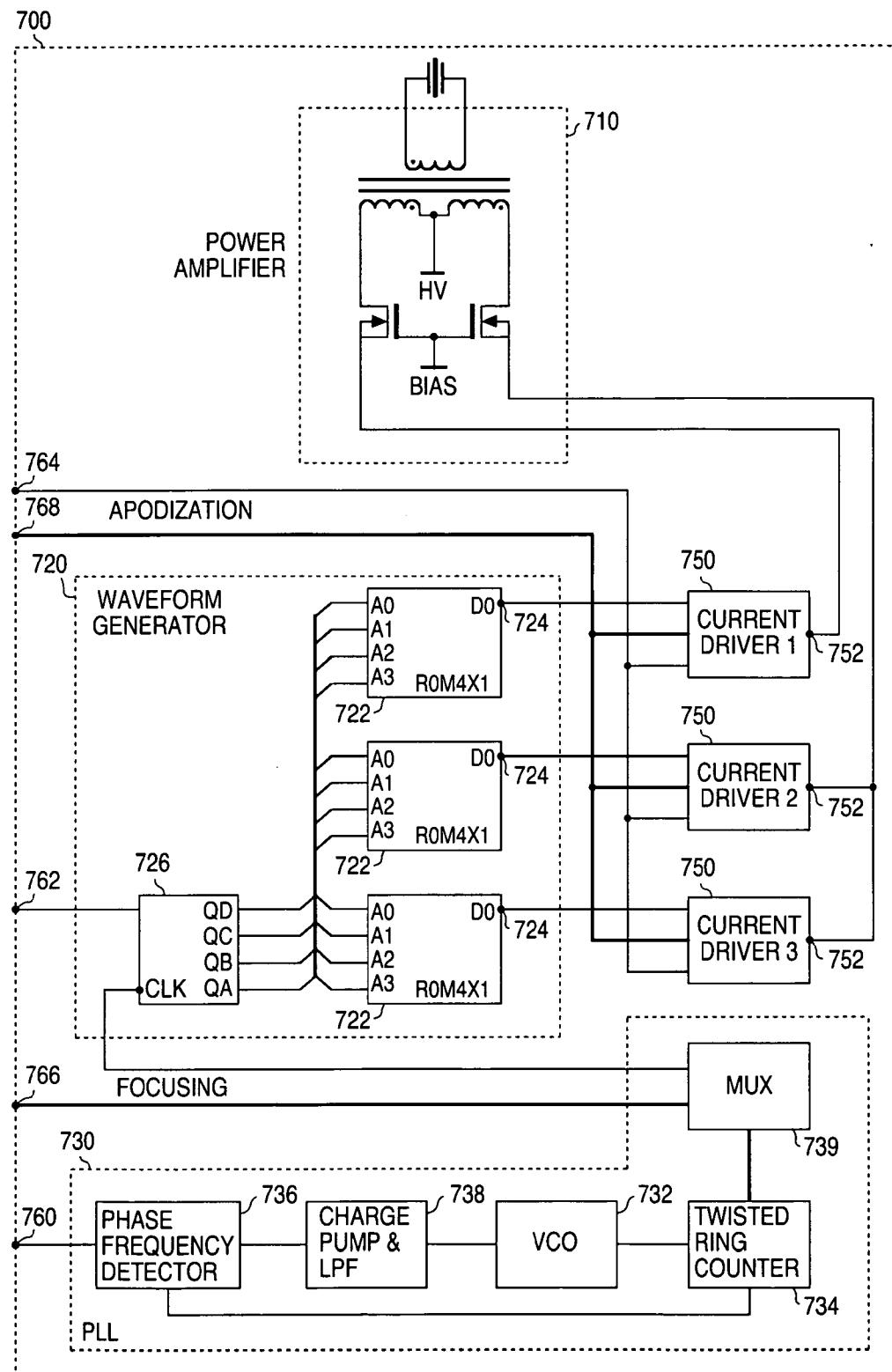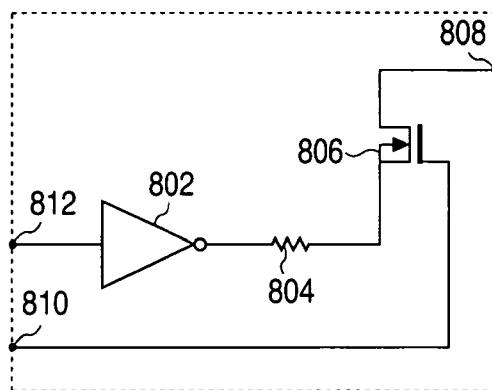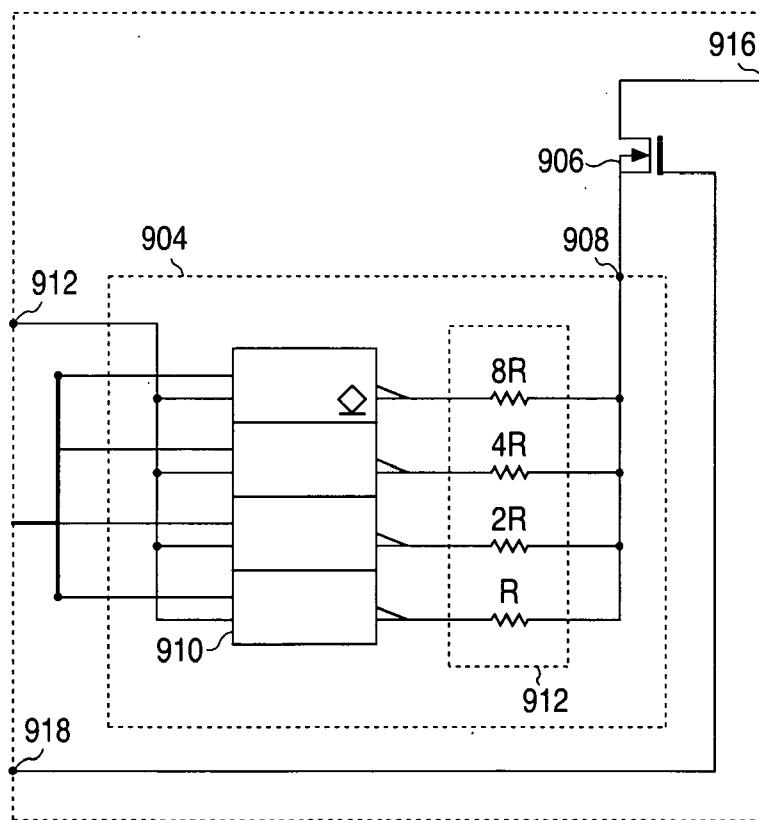
1st (a), 2nd (b), and 3rd (c) Base Waveforms & Their Combining (d, e)

FIG. 5

FIG. 6

5/6

FIG. 7

FIG. 8

FIG. 9

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - A61B 8/00; A61B 8/14
USPC - 600/437; 600/472

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
USPC - 600/437,472
IPC(8) - A61B 8/00; A61B 8/14

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
600/444, 447

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PubWest (US Pat., US PGPUB, EPO, JPO, US OCR), IEEE Proceedings (IEEE.org's IEEE Explorer): Key terms searched:
Beamforming, Waveform, Gaussian envelop, ultrasound, acoustic, polarity, inverse, inverted, bipolar, unipolar, uniform amplitude, NAND
gate, PLL, Phase Lock Loop, apodization, apodizing

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 5,928,151 A (Hossack et al.) 27 July 1999 (27.07.1999) col. 1, ln46-58; col. 2, ln 14-16; col. 6, ln 4-14; col. 7, ln 25-40; col. 10, ln 44-61; col. 11, ln 22-51	1, 2, 4, 6, and 8 --------- 3, 5, 7, 9, 10
Y	US 7,074,186 B2 (Loftman et al.) 11 July 2006 (11.07.2006) col. 5, ln 24-44; col. 6, ln 1-49	3, 5, 7, and 9
Y	US 2006/0238527 A1 (Walker et al.) 26 October 2006 (26.10.2006) para [0023]	10, 13, 15-20
Y	US 6,016,285 A (Wright et al.) 18 January 2000 (18.01.2000) col. 5, ln 16-21; col. 10, ln 8-15; col. 16, ln 33-42; col. 18, ln 3-62; col. 21, ln 64-67; col. 22, ln 5-13)	11-20
Y	US 7,107,159 B2 (German) 12 September 2006 (12.09.2006) col. 13, ln 1-8	11-20
Y	US 6,312,379 B1 (Bradley et al.) 06 November 2001 (06.11.2001) col. 2, ln 17-31; col. 6, ln 27-36; FIGS. 2, 3, and 10	12
Y	US 2005/0195103 A1 (Davis et al.) 08 September 2005 (08.09.2005) FIGS. 5, 9, 10, and 16	14
P	US 2007/0211786 A1 (Shattil) 13 September 2007 (13.09.2007)	11-20
P	US 2007/0239001 A1 (Mehi et al.) 11 October 2007 (11.10.2007)	11-20

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	
"E" earlier application or patent but published on or after the international filing date	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 July 2008 (23.07.2008)	0 1 AUG 2008

Name and mailing address of the ISA/US	Authorized officer:
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450	Lee W. Young
Facsimile No. 571-273-3201	PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (April 2007)

专利名称(译)	用于医学超声成像中的换能器激发的方法和装置		
公开(公告)号	EP2131743A1	公开(公告)日	2009-12-16
申请号	EP2008727132	申请日	2008-03-25
[标]申请(专利权)人(译)	超科有限公司		
申请(专利权)人(译)	Supertex公司，公司		
当前申请(专利权)人(译)	Supertex公司，公司		
[标]发明人	LAZAR SHIFRIN A		
发明人	LAZAR, SHIFRIN, A.		
IPC分类号	A61B8/00 A61B8/14 G01S7/52 G01S15/89 G10K11/34		
CPC分类号	G01S7/52046 G01S15/895 G10K11/346		
优先权	12/053235 2008-03-21 US 60/920606 2007-03-29 US		
其他公开文献	EP2131743A4		
外部链接	Espacenet		

摘要(译)

一种医学超声成像中换能器激发的方法。基于高斯调制余弦的阶梯近似，发射波形提供带限频谱和低水平的二阶谐波，同时在两个载波周期内保持发射的持续时间。波形被构造为四个单极矩形脉冲的线性组合，其单位幅度。此外，所描述的实施例支持数字控制的发送切趾和聚焦。