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(54) Title: HIGH-SPEED PULSE SHAPING FILTER SYSTEMS AND METHODS

(57) Abstract: A first system and method relates to an analog current-mode method using branch systems. In the analog current-mode implementation, multiple branches can be scaled according to filter coefficients and switched using known data points. Positive coefficients can add current to the summing node, while negative coefficients can remove current from the summing node. Switches can be implemented with quick charge or discharge paths in order to operate at very high data rates. A second system and method relates to a digital look-up table based high-speed implementation. In the digital implementation, outputs can be pre-calculated as an n-bit output word that drives an n-bit DAC. Each bit of the n-bit word can then be described as an independent function of the known data points. Each such function can be implemented as a high-speed combinational logic block.



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HIGH-SPEED PULSE SHAPING FILTER SYSTEMS AND METHODS

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit under 35 U.S.C. § 119(e) of U.S. Provisional Patent Application No. 60/991,830, filed on 03 December 2007, the entire contents and substance of which is hereby incorporated by reference as if fully set forth below.

BACKGROUND

Pulse shaping filters are filters used in digital communications. In digital telecommunications, for instance, pulse shaping is the process of altering a waveform of transmitted pulses. One purpose of a pulse shaping filter is to change the transmitted signal to suit better communication channels by limiting the effective bandwidth of the transmission. In essence, by filtering the transmitted pulses, the interference caused by the channel can be controlled and/or reduced.

In addition, pulse shaping is used to increase transmission data rates without increasing the bandwidth or the bit error rate of the signal. Preferably, the pulse shape used for transmission has a low bandwidth and no inter-symbol interference (ISI). A sinc function includes both of these properties and thus can significantly increase spectral efficiency. A system using sinc functionality for pulse shaping can be susceptible to timing jitter - thus is not practical - and is challenging to precisely implement. A rectangular wave, on the other hand, is not sensitive to timing jitter, but requires a large bandwidth. Commonly-used pulse shapes, such as raised cosine, can provide a compromise between the two extremes of the sinc function and the rectangular wave.

With the advent of multi-media streaming and other high data throughput applications, the required speed of operation of pulse shaping filters is growing. Conventional finite impulse response (FIR) implementations are no longer sufficient to meet these requirements.

For example, **Fig. 1** illustrates a block diagram of a conventional pulse shaping filter **10** having an upsampling factor of 2, which is capable of operating up to a few mega bits per second (Mbps). The pulse shaping filter **10** of **Fig. 1** includes a delay system **20**, a multiplier system **40**, and an adding system **60**.

The pulse shaping filter **10** can receive an input signal **12**. Upon receipt, the input signal **12** is delayed by a predetermined number of delays blocks with delays of half the symbol rate **24** of the delay system **20**. As illustrated in **Fig. 1**, the delays **24** are chained together to make up

the delay system **20**. Each tap **22**, after going through the delay **24**, is output to a multiplier **42** of the multiplier system **40**. Each multiplier **42** receives both a coefficient (i.e., c_i) and a signal **26** from the different delayed versions of the input signal **12**. The multiplier **42** multiplies the coefficient (i.e., c_i) by the signal **26** received from the delay **24**. Each of the outputs **44** of the multiplier **42** are input into the adding system **60**, which then sums for an output **16** of the PSF **10**.

Considering that a 13-tap raised cosine filter for a 2 giga bits per second (Gbps) wireless transmission having an upsampling factor of two the filter has to operate at 4 Giga Hertz (GHz). Unfortunately, a digital FIR implementation using multipliers and adders is not possible; it requires challenging multiplication which takes excessive power and due to the mathematics necessary for calculations will delay processing. Alternate filter implementations are required which can support such high data-rates.

SUMMARY

A first system and method relates to an analog current-mode method using branch systems. In the analog current-mode implementation, multiple branches systems can be scaled according to filter coefficients and switched using known data points. Positive coefficients can add current to the summing node, while negative coefficients can remove current from the summing node. Switches can be implemented with quick charge/discharge paths in order to operate at very high data rates. A second system and method relates to a digital look-up table based high-speed implementation. In the digital implementation, outputs can be pre-calculated as an n-bit output word that drives an n-bit DAC. The digital implementation is accomplished by splitting the processing paths into two paths, which effectively reduces the size of the lookup table from 2^m to $2^{(m-1)/2}$ for an m-tap filter implementation. Each bit of the n-bit word can then be described as an independent function of the known $(m-1)/2$ data points. Each such function can be implemented as a high-speed combinational logic block. Both systems and methods enable the implementation of pulse shaping filters for multi-gigabit per second data transmission.

These and other objects, features, and advantages of embodiments of the present invention will become more apparent upon reading the following specification in conjunction with the accompanying drawing figures.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a block diagram of a conventional pulse shaping filter.

Fig. 2 is a block diagram of a pulse shaping filter, in accordance with an exemplary embodiment of the present invention.

Fig. 3 is a schematic of a delay system, in accordance with an exemplary embodiment of the present invention.

Fig. 4 is a schematic of a multiplier system, in accordance with an exemplary embodiment of the present invention.

Fig. 5 is a schematic of a summing system, in accordance with an exemplary embodiment of the present invention.

Fig. 6 is a graphical representation of a simulated eye-diagram of a differential pulse shaping filter implementation with an analog process, in accordance with an exemplary embodiment of the present invention.

Fig. 7 is a graphical representation of a simulated baseband signal spectrum before and after entering the pulse shaping filter, in accordance with an exemplary embodiment of the present invention.

Fig. 8 is a schematic of a cosine pulse shaping filter in a digital implementation, in accordance with an exemplary embodiment of the present invention.

Fig. 9 is a schematic of a delay system for generating a six-bit address, in accordance with an exemplary embodiment of the present invention.

Fig. 10 is a graphical representation of a simulated eye-diagram of a cosine pulse shaping filter implementation with a digital process, in accordance with an exemplary embodiment of the present invention.

Fig. 11 is a graphical representation of a signal spectrum before and after filtering, in accordance with an exemplary embodiment of the present invention.

DETAILED DESCRIPTION

To facilitate an understanding of the principles and features of various embodiments of the present invention, they are explained hereinafter with reference to their implementation in an illustrative embodiment. In particular, illustrative embodiments of the invention are described in the context of being a pulse shaping filter.

For example, at least two systems and methods to implement high-speed pulse shaping filters are disclosed herein. A first system and method relates to an analog current-mode method using branch systems, i.e., switched current-mirrors. A second system and method relates to a

digital look-up table based high-speed implementation. Both of these methods enable the implementation of pulse shaping filters for multi-gigabit per second data transmission.

In the analog current-mode implementation, multiple current mirror branches can be scaled according to the filter coefficients and switched using present and prior data points. Positive coefficients are implemented as branches that add can current to the summing node, while negative coefficients are implemented as branches that can remove current from the summing node. The switches can be implemented with quick charge/discharge paths in order to operate at very high data rates.

In the digital implementation, the outputs can be pre-calculated as an n-bit output word that drives an n-bit digital-to-analog converter (DAC). Each bit of the n-bit word can then described as an independent function of the present and prior data points. Each such function can be implemented as a high-speed combinational logic block. Splitting the coefficients into two sets (even and odd) reduces the size of the lookup table by approximately half.

Embodiments of the invention are not, however, limited to a pulse shaping filter. Embodiments of the present invention can be used to provide a filter system.

The materials and components described hereinafter as making up the various elements of the present invention are intended to be illustrative and not restrictive. Many suitable materials and components that would perform the same or a similar function as the materials and components described herein are intended to be embraced within the scope of the invention. Further, such other materials not described herein can include, but are not limited to, materials that are developed after the time of the development of the invention, for example.

Referring now to the figures, wherein like reference numerals represent like parts throughout the view, embodiments of the present invention will be described in detail.

As illustrated in **Figs. 2-5**, exemplary embodiments of the present invention relate to a system and method of implementing a pulse shape filter **100** in the analog domain. The system and method builds from the blocks of the conventional pulse shape filter, i.e., at least an input signal, a delay system, a multiplier system, and an adder system.

As illustrated in **Fig. 2**, the pulse shape filter **100** comprises an input signal **102**, a delay system **200**, a multiplier system **300**, and an adding or summing system **400**. An exemplary embodiment of the delay system **200** is illustrated in **Fig. 3**, an exemplary embodiment of the multiplier system **300** is illustrated in **Fig. 4**, and an exemplary embodiment of the adding or

summing system **400** is illustrated in **Fig. 5**. The exemplary embodiments illustrated in **Figs. 3-5** illustrate characteristics that are desirable for an exemplary implementation, such that the duplications illustrated can be increased or decreased based on the number of taps and the number of non-zero coefficients.

The delay system **200** includes a plurality of delays **210**. For instance, the delay system **200** can include a digital delay chain with half of the symbol period being required first, wherein $\tau_s/2$. As shown in **Fig. 3**, this delay chain can be implemented with a plurality of D-flipflops **215**. The delay system **200** can receive the data signal **220**, the clock signal (CLK) **222**, and the CLK_BAR signal **224**, all from the input signal **102**.

As illustrated in **Fig. 3**, each D-flip flop includes at least a D input, a Q output, and a clock (CLK) input. In an exemplary embodiment, the data **220** from the input signal **102** is coupled to the D input **215AD** of a first D-flipflop **215A**. The CLK signal **222** from the input signal **102** is coupled to a clock input **215AC** of the first D-flipflop **215A**. A Q output **215AQ** of the first D-flipflop **215A** is a first input **232A** of a second AND gate **232** and the CLK_BAR input **224** is a second input **232B** of the second AND gate **232**. The single output **232o** of the second AND gate **232** is a data point (e.g., **C4**).

The number of D-flipflops required in the delay system **200** can be determined by the position of the last non-zero coefficient. For example, as illustrated in **Fig. 3**, five non-zero coefficients are present.

In an exemplary embodiment wherein there are five non-zero coefficients, data **220** from the input signal **102** is coupled to a first input **230A** of a first AND gate **230** and the CLK_BAR signal **224** is coupled to a second input **230B** of the first AND gate **230**. The output **230o** of the first AND gate **230** is a first data point (e.g., **C2**). In addition, data **220** from the input signal **102** is coupled to the D input **215AD** of a first D-flipflop **215A**. The CLK signal **222** from the input signal **102** is coupled to the clock input **215AC** of the first D-flipflop **215A**. A Q output **215AQ** of the first D-flipflop **215A** is a first input **232A** to the second AND gate **232** and the CLK_BAR input **224** from the input signal **102** is the second input **232B** to the second AND gate **232**. The single output **232o** of the second AND gate **232** is a second data point (e.g., **C4**). The Q output **215AQ** of the first D-flipflop **215A** is coupled to a D input **215BD** of a second D-flipflop **215B**. The CLK signal **222** is coupled to the clock input **215BC** of the second D-flip flop **215B**. The Q output **215BQ** is coupled to a first input **234A** of a third AND gate **234** and the CLK_BAR

signal **224** is coupled to a second input **234B** of the third AND gate **234**. An output **234o** of the third AND gate **234** is a third data point (e.g., **C6**). Further, the Q output **215BQ** of the second D-flipflop **215B** is a first input **236A** to a fourth AND gate **236** and the CLK signal **222** is a second input **236B** to the fourth AND gate **236**. An output **236o** of the fourth AND gate **236** is a fourth data point (e.g., **C5**). The Q output **215BQ** of the second D-flipflop **215B** is coupled to a D input **215CD** of a third D-flipflop **215C**. The CLK signal **222** is coupled to a clock input **215CC** of the third D-flipflop **215C**. A Q output **215CQ** of the third D-flipflop **215C** is a first input **238A** to a fifth AND gate **238** and the CLK_BAR signal **224** is a second input **238B** of the fifth AND gate **238**. An output **238o** of the fifth AND gate **238** is a fifth data point (e.g., **C8**).

Each of the data points **230o**, **232o**, **234o**, **236o**, and **238o** (i.e., **C2**, **C4**, **C5**, **C6**, and **C8**) are coupled to the multiplier system **300**, as illustrated in **Fig. 4**.

Fig. 4 illustrates the multiplier system **300**. The multiplier system **300** includes a current reference branch **305** that is coupled to at least one branch system **310**. The number of branch systems **310** in the multiplier system **300** can be dependent on the number of non-zero coefficients. As illustrated in **Fig. 4**, in an exemplary embodiment, there are five non-zero coefficients. Each branch system **310** includes at least one NMOS transistor (**Ni**) comprising a drain, a gate, and a source; at least one NMOS switch (**Si**) comprising a drain, a gate, and a source; and at least one PMOS transistor (**Pi**) comprising a source, a gate, and a drain.

In its simplest implementation, the multiplier system **300** includes a current reference branch **305** and a single branch system **310**. In such an example, the current reference branch **305** comprises a current **301**, a transistor **302**, a NMOS transistor **304**, a NMOS switch **306**, and a PMOS transistor **308**.

As shown in **Fig. 4**, the current (**Ibias**) **301** can be received by the current reference branch **305**. The current (**Ibias**) **301** is coupled to a drain **302D** (please correct in figure also) and a gate **302G** of a transistor **302** (**B1**). The source **302S** of the transistor **302** (**B1**) is coupled to a ground **303**. The gate **302G** of the transistor **302** (**B1**) is coupled to a gate **304G** of an NMOS transistor **304** (**N1**), which is coupled to a gate node **309**. A source **304S** of the NMOS transistor **304** (**N1**) is coupled to the ground **303**. A drain **304D** of the NMOS transistor **304** (**N1**) is coupled to a source **306S** of a NMOS switch **306** (**S1**). A gate **306G** of the NMOS switch **306** (**S1**) is coupled to the voltage supply **307**. A drain **306D** of the NMOS switch (**S1**) is

coupled to a drain **308D** and a gate **308G** of the PMOS transistor **308 (P1)** and the voltage **409 (Vbias)**. The source **308S** of the PMOS transistor **308 (P1)** is coupled to the voltage supply **307**.

The branch system **310** comprises at least a PMOS transistor (**Pi**) comprising a source, a gate, and a drain; a NMOS switch (**Si**) comprising a drain, a gate, and a source; a NMOS transistor (**Ni**) comprising a drain, a gate, and a source; and a transistor (**Di**) comprising a source, a gate, and a drain.

A first branch system **312** receives a first non-zero (e.g., negative) coefficient (i.e., **C2**) that is coupled to a gate **326G** of a NMOS switch **326 (S2)** and a gate **322G** of a transistor **322 (D2)**. A drain **322D** of the transistor **322 (D2)** is coupled to the ground **303** and a source **322S** of the transistor **322 (D2)** is coupled to a gate **324G** of a NMOS transistor **324 (N2)** and a drain **324D** of the NMOS transistor **324 (N2)**. The source **324S** of the NMOS transistor **324 (N2)** is coupled to the ground **303**, and the drain **324D** of the NMOS transistor **324 (N2)** is coupled to an output **312o (V2)**. The gate **324G** of the NMOS transistor **324 (N2)**, the source **322S** of the transistor **322 (D2)**, and a source **326S** of the NMOS switch **326 (S2)** are also coupled to the output **312o (V2)**. The drain **326D** of the NMOS switch **326 (S2)** is coupled to a drain **328D** of the PMOS transistor **328 (P2)**. A gate **328G** of the PMOS transistor **328 (P2)** is coupled to the voltage **409 (Vbias)**. The source **328S** of the PMOS transistor **328 (P2)** is coupled to the voltage supply **307**.

A second branch system **314** receives a second non-zero (e.g., positive) coefficient (i.e., **C4**), which is coupled to a gate **332G** of a transistor **332 (D4)** and a gate **336G** of a NMOS switch **336 (S4)**. A source **332S** of the transistor **332 (D4)** is coupled to the voltage supply **307** and the drain **332D** of the transistor **332** is coupled to a gate **338G** of a PMOS transistor **338 (P4)** and a drain **338D** of the PMOS transistor **338 (P4)**. A source **338S** of the PMOS transistor **338 (P4)** is coupled to the voltage supply **307**. The gate **338G** of the PMOS transistor **338 (P4)**, and thus the drain **332D** of the transistor **332 (D4)**, are coupled to an output of the branch **314o (V4)** and a drain **336D** of the NMOS switch **336 (S4)**. A source **336S** of the NMOS switch (**S4**) is coupled to a drain **334D** of a NMOS transistor **334 (N4)**. A gate **334G** of the NMOS transistor **334 (N4)** is coupled to the gate **304G** of the NMOS transistor **304 (N1)**, i.e., a gate node **309**. A source **334S** of the NMOS transistor **334 (N4)** is coupled to the ground **303**.

A third branch system **316** receives a third non-zero (e.g., positive) coefficient (i.e., **C5**), which is coupled to a gate **342G** of a transistor **342 (D5)** and a gate **346G** of a NMOS switch **346**

(S5). A source **342S** of the transistor **342 (D5)** is coupled to the voltage supply **307** and the drain **342D** of the transistor **342** is coupled to a gate **348G** of a PMOS transistor **348 (P5)** and a drain **348D** of the PMOS transistor **348 (P5)**. A source **348S** of the PMOS transistor **348 (P5)** is coupled to the voltage supply **307**. The gate **348G** of the PMOS transistor **348 (P5)**, and thus the drain **342D** of the transistor **342 (D5)**, are coupled to an output of the branch **316o (V5)** and a drain **346D** of the NMOS switch **346 (S5)**. A source **346S** of the NMOS switch (S5) is coupled to a drain **344D** of a NMOS transistor **344 (N5)**. A gate **344G** of the NMOS transistor **344 (N5)** is coupled to the gate **304G** of the NMOS transistor **304 (N1)**, i.e., a gate node **309**, and the gate **334G** of the NMOS transistor **334 (N4)**. A source **344S** of the NMOS transistor **344 (N5)** is coupled to the ground **303**.

A fourth branch system **318** receives a fourth non-zero (e.g., positive) coefficient (i.e., **C6**), which is coupled to a gate **352G** of a transistor **352 (D6)** and a gate **356G** of a NMOS switch **356 (S6)**. A source **352S** of the transistor **352 (D6)** is coupled to the voltage supply **307** and the drain **352D** of the transistor **352** is coupled to a gate **358G** of a PMOS transistor **358 (P6)** and a drain **358D** of the PMOS transistor **358 (P6)**. A source **358S** of the PMOS transistor **358 (P6)** is coupled to the voltage supply **307**. The gate **358G** of the PMOS transistor **358 (P6)**, and thus the drain **352D** of the transistor **352 (D6)**, are coupled to an output of the branch **318o (V6)** and a drain **356D** of the NMOS switch **356 (S6)**. A source **356S** of the NMOS switch (S6) is coupled to a drain **354D** of a NMOS transistor **354 (N6)**. A gate **354G** of the NMOS transistor **354 (N6)** is coupled to the gate **304G** of the NMOS transistor **304 (N1)**, i.e., a gate node **309**, and the gate **334G** of the NMOS transistor **334 (N4)**. A source **354S** of the NMOS transistor **354 (N6)** is coupled to the ground **303**.

A fifth branch system **320** receives a fifth non-zero (e.g., negative) coefficient (i.e., **C8**), which is coupled to a gate **366G** of a NMOS switch **366 (S8)** and a gate **362G** of a transistor **362 (D8)**. A drain **362D** of the transistor **362 (D8)** is coupled to the ground **303** and a source **362S** of the transistor **362 (D8)** is coupled to a gate **364G** of a NMOS transistor **364 (N8)** and a drain **364D** of the NMOS transistor **364 (N8)**. The source **364S** of the NMOS transistor **364 (N8)** is coupled to the ground **303**, and the drain **364D** of the NMOS transistor **364 (N8)** is coupled to an output **320o (V8)**, which is also coupled to the source **362S** of the transistor **362 (D8)** and the gate **364G** of the NMOS transistor **364 (N8)**. Accordingly, the gate **364G** of the NMOS transistor **364 (N8)**, the source **362S** of the transistor **362 (D8)**, the drain **364D** of the NMOS

transistor **364** (N8) and a source **366S** of the NMOS switch **366** (S8) are all coupled to the output **312o** (V8). The drain **366D** of the NMOS switch **366** (S8) is coupled to a drain **368D** of the PMOS transistor **368** (P8). The gate **368G** of the PMOS transistor **368** (P8) is coupled to the voltage **409** (Vbias). The source **368S** of the PMOS transistor **368** (P8) is coupled to the voltage supply **307**.

The adding system **400** collects the outputs of all the branch systems **310**, e.g., branch systems **312**, **314**, **316**, **318**, and **320**, or outputs **312o**, **314o**, **316o**, **318o**, and **320o**, respectively. The adding system can sum the outputs. As shown in **Fig. 5**, the adding system **400** can include a number of transistors and/or a number of resistors for summing the outputs of the branch systems.

As illustrated, the output **312o** (V2) of the first branch **312** is coupled to a gate **402G** of a first transistor **402** (M2), a drain **402D** of the first transistor **402** (M2) is coupled to a first node **405**, and a source **402S** of the first transistor **402** (M2) is coupled to a ground **403**. The output **314o** (V4) of the second branch system **314** is coupled to the gate **404G** of a second transistor **404** (M4), a source **404S** of the second transistor **404** (M4) is coupled to a voltage supply **401**, and a drain **404D** of the second transistor **404** (M4) is coupled to the first node **405**. The output **316o** (V5) of the third branch system **316** is coupled to the gate **406G** of a third transistor **406** (M5), a source **406S** of the third transistor **406** (M5) is coupled to a voltage supply **401**, and a drain **406D** of the third transistor **406** (M5) is coupled to the first node **405**. The output **318o** (V6) of the fourth branch system **318** is coupled to the gate **412G** of a fourth transistor **412** (M6), a source **412S** of the fourth transistor **412** (M6) is coupled to a voltage supply **401**, and a drain **412D** of the fourth transistor **412** (M6) is coupled to the first node **405**. The output **320o** (V8) of the fifth branch **320** is coupled to a gate **408G** of a fifth transistor **408** (M8), a drain **408D** of the fifth transistor **408** (M8) is coupled to the first node **405**, and a source **408S** of the fifth transistor **408** (M8) is coupled to the ground **403**. The voltage **409** (Vbias) is coupled to a gate **414G** of a PMOS transistor **414** (P7), a source **414S** of the PMOS transistor **414** (P7) is coupled to the voltage supply **401**, and the drain **414D** of the PMOS transistor **414** (P7) is coupled to the first node **405**. The first node **405** is coupled to the drain **410D** and the gate **410G** of the transistor **410** (N7). The source **410S** of the transistor **410** (N7) is coupled to the ground **403**. The first node **405** is coupled to a gate **416G** of a first NMOS transistor **416** (N3), a drain **416D** of the NMOS transistor **416** (N3) is coupled to a first end **420A** of a first resistor **420** (R1), a source

416S of the NMOS transistor **416 (N3)** is coupled to the ground **403**. A second end **420B** of the first resistor **420 (R1)** is coupled to the voltage supply **401**. The first end **420A** of the first resistor **420 (R1)** is also coupled to the gate **418G** of a second NMOS transistor **418 (N10)**, a drain **418D** of the second NMOS transistor (**N10**) is coupled to the output **499** of the adding system **400**, and a source **418S** of the second NMOS transistor **418 (N10)** is coupled to the ground **403**. A second resistor **422 (R2)** is coupled at a first end **422A** to the voltage supply **401** and at a second end **422B** to the output **499** of the adding system **400**.

Example And Operation of Pulse Shape Filter 100

For example, for the pulse shape filter **100** consider a raised cosine pulse shaping filter implementation with nine taps having a roll-off factor of 0.25 with an upsampling factor of 2. For this example, the coefficients are predetermined as:

C1	-0.000
C2	-0.1856
C3	0.0000
C4	0.6274
C5	1.0000
C6	0.6274
C7	0.0000
C8	-0.1856
C9	-0.000

Of the nine coefficients, five are non-zero coefficients.

The input signal **102** enters the delay system **200** comprising digital delay chain with half the symbol period ($\tau_s/2$). As shown in **Fig. 3**, this can be implemented with at least three D-flipflops **215**. The delayed outputs are applied to AND gates as a first input along with either the CLK or CLK_BAR signals as the second input, so as to realize upsampling. In this example, only five data points are required because there are only five non-zero coefficients (see above). The actual implementation can have extra delay elements in the clock and data paths so as to compensate for unequal delays in different paths. Using the five data points generated by the digital delay line, the pulse-shaping filter is implemented using switched branch systems (i.e., current mirrors) shown in **Fig. 4**.

Each current mirror branch or branch system **310** in **Fig. 4** includes at least one an NMOS transistor (N_i), an NMOS switch (S_i), and a PMOS transistor (P_i). In the branches representing negative coefficients **C2** and **C8** (i.e., branch systems **312** and **320**), the current is set by its PMOS transistor (i.e., PMOS transistor **328** (**P2**) and PMOS transistor **368** (**P8**), respectively). The NMOS switches **326** (**S2**) and **366** (**S8**) are controlled by the data points **C2** and **C8** from derived from the delay system **200** (see, e.g., **Fig. 3**). The diode-connected NMOS transistors **324** (**N2**) and **364** (**N8**) can generate the control voltages **V2** and **V8** (or outputs **312o** and **320o** of the branch systems **312** and **320**, respectively) that determine if the appropriate currents have to be steered away from the drain current of the diode-connected NMOS transistor **410** (**N7**) in **Fig. 5**.

Still referring to **Fig. 4**, in the branch systems representing the positive coefficients (i.e., branch systems **314**, **316**, and **318**), the current is set by the signals **C4**, **C5**, and **C6** and the NMOS transistors **334** (**N4**), **344** (**N5**), and **354** (**N6**), respectively. The NMOS switches **336** (**S4**), **346** (**S5**), and **356** (**S6**) can be controlled by data points **C4**, **C5**, and **C6** derived from the delay system (see e.g. **Fig. 3**). The PMOS transistors **338** (**P4**), **348** (**P5**), and **358** (**P6**) can generate the control voltages **V4**, **V5**, and **V6** (or outputs **314o**, **316o**, and **318o** of the branch systems **314**, **316**, and **318**, respectively) to add appropriately scaled currents to the NMOS transistor **410** (**N7**) in **Fig. 5** using transistors **404** (**M4**), **406** (**M5**), and **412** (**M6**). Accordingly, the current summing can be implemented in the diode-connected NMOS transistor **410** (**N7**). The output current is mirrored into the NMOS transistors **416** (**N3**), converted into a voltage level - using the first resistor **420** (**R1**) - and then amplified again by using the NMOS transistor **418** (**N10**) and the second resistor **422** (**R2**).

Referring back to **Fig. 4**, in order to enable operation at multi-giga bits per second, auxiliary charging and discharging paths are provided using PMOS transistors **322** (**D2**), **332** (**D4**), **342** (**D5**), **352** (**D6**), and **362** (**D8**). These transistors improve the output voltage waveform when operating at high speeds. The simulated eye-diagram of a differential pulse-shaping filter implemented using switched current mirrors (i.e., branch systems) (see **Fig. 4**) and delay chain (**Fig. 3**) is depicted in **Fig. 6**. A differential structure can avoid clock leakage into the output spectrum. The spectrum of the signals before and after pulse shaping is shown in **Fig. 7**. Notably, **Figs. 6-7** are simulated with a 1.9 Gbps symbol rate.

As illustrated in **Figs. 8-9**, exemplary embodiments of the present invention relate to a system and method of implementing a pulse shape filter **200** in the digital domain. The system and method implement a look-up table of the size $2^{(m-1)/2}$ for this m-tap pulse shape filter in the digital domain.

In the analog system (e.g., pulse shape filter **100**), i.e., the switched current mirror implementation or the branch system implementation, the upsampling can be achieved in the delay chain shown in **Fig. 3**. Another system and method to implement upsampling by a factor of N is to have N parallel paths and then do a parallel to serial conversion at the end.

As shown in **Fig. 8**, the pulse shape filter **200** is illustrated in an exemplary embodiment. The number of paths, illustrated in **Fig. 8** as having six paths, can vary depending on the desired accuracy of the output digital to analog converter.

In an exemplary embodiment, the pulse shape filter **200** in a digital domain includes a delay system **900**, a processing system **1000**, and a n-bit digital to analog (DAC) converter **1100**.

An input signal **802** includes both a data signal **804** and a CLK signal **806**. The data signal **804** is coupled to a first input of the delay system **900**, and the CLK signal **806** is coupled to a second input of the delay system **900**. For example, as illustrated in **Fig. 9**, the delay system **900** can include a plurality of D-flipflops. In an exemplary embodiment, the delay system **900** can be referred to as a digital delay line comprising a plurality of D-flipflops daisy chained together. In an exemplary embodiment, the number of D-flipflops is dependent on the number of filter taps. For example, as illustrated in **Fig. 9**, there can be six D-flipflops in the 13-tap pulse shaping filter being implemented.

The data signal **804** is coupled to a D input **905D** of a first D-flipflop **905**. The CLK signal **806** is coupled to a clock input **905C** of the first D-flipflop **905**. A Q output **905Q** of the first D-flipflop **905** is a first data point (**d0**). The Q output **905Q** of the first D-flipflop **905** is coupled to a D input **910D** of a second D-flipflop **910**. The CLK signal **806** is coupled to a clock input **910C** of the second D-flipflop **910**. A Q output **910Q** of the second D-flipflop **910** is a second data point (**d1**). The Q output **910Q** of the second D-flipflop **910** is coupled to a D input **915D** of a third D-flipflop **915**. The CLK signal **806** is coupled to a clock input **915C** of the third D-flipflop **915**. A Q output **915Q** of the third D-flipflop **915** is a third data point (**d2**). The Q output **915Q** of the third D-flipflop **915** is coupled to a D input **920D** of a fourth D-flipflop **920**. The CLK signal **806** is coupled to a clock input **920C** of the fourth D-flipflop **920**. A Q

output **920Q** of the fourth D-flipflop **920** is a fourth data point (**d3**). The Q output **920Q** of the fourth D-flipflop **920** is coupled to a D input **925D** of a fifth D-flipflop **925**. The CLK signal **806** is coupled to a clock input **925C** of the fifth D-flipflop **925**. A Q output **925Q** of the fifth D-flipflop **925** is a fifth data point (**d4**). The Q output **925Q** of the fifth D-flipflop **925** is coupled to a D input **930D** of a sixth D-flipflop **930**. The CLK signal **806** is coupled to a clock input **930C** of the sixth D-flipflop **930**. A Q output **930Q** of the sixth D-flipflop **930** is a sixth data point (**d5**).

The outputs from the delay system **900** are the delayed versions of the input bit stream. Each DAC input bit in **Fig. 8**, e.g., **b0**, **b1**, **b2**, **b3**, **b4**, and **b5**, is an output of the processing system 1000, which is a function of the outputs of **900**. Each DAC input bit can be evaluated using *Even* paths and *Odd* paths, based on its numbered coefficient. As a result, by processing the outputs of the delay chain, the size of the lookup table can be reduced from 2^m to $2^{(m-1)/2}$ for an m-tap pulse shaping filter. These signals are ultimately input into a MUX with the CLK signal **806** which performs the upsampling. A 2-input MUX can perform an upsampling by a factor of 2. Similarly, an N-input MUX can perform an upsampling by a factor of N. Each of these outputs is a bit to the n-bit DAC **1100**. The output **999** of the DAC is also the output of the pulse shaping filter **800**.

Example And Operation of Pulse Shape Filter 200

For example, this technique can be used in implementing a 13-tap raised cosine filter with a roll-off factor of 0.3235. The tap coefficients in this example are:

C1	0.0000
C2	0.0650
C3	-0.0000
C4	-0.1691
C5	0.0000
C6	0.6212
C7	1.0000
C8	0.6212
C9	0.0000
C10	-0.1691
C11	-0.0000
C12	0.0650
C13	0.0000

Because the upsampling factor is two, the coefficients are divided into two sets:

Odd: [0.0000 (C1), 0.0000 (C3), 0.0000 (C5), 1.0000 (C7), 0.0000 (C9), 0.0000 (C11), 0.0000 (C13)]; and

Even: [0.0650 (C2), -0.1691(C4), 0.6212 (C6), 0.6212 (C8), -0.1691 (C10), 0.0650 (C12)]

Because there is a single non-zero coefficient in the *Odd set*, the output of this path is solely **C7**, which is the input data delayed by three time periods. The output of the *Even path* can be any one of the 2^6 possible outcomes because there are six non-zero coefficients. For example if the last bits were all 1s, the output would be:

$$0.0650 - 0.1691 + 0.6212 + 0.6212 - 0.1691 + 0.0650 = 1.0342 \text{ and so on.}$$

In operate to run at extremely high speeds, all the possible 2^6 outcomes can be precalculated and stored at addresses representing the last 6 data inputs. Table 1 (below) lists all the possible outcomes as 6 bit binary numbers (obtained after scaling and adding a bias). Also shown at the bottom of Table 1, are the 2 possible outcomes of the *odd path*.

Address	Outcome	
000000	010101	} <i>Even Coefficients Outcomes</i>
000001	010111	
000010	010000	
⋮	⋮	
111101	111010	
111110	110011	
111111	110101	
Odd (d3=0)	010101	} <i>Odd Coefficients Outcomes</i>
Odd (d3=1)	110100	

Table 1

Precalculated 6 bit outcomes for all possible 6 bit data inputs. Also shown are the 2 possible outcomes of the *odd path*.

The digital delay chain implementing the 6-bit address is illustrated in **Fig. 9**. Each of the precalculated outcomes in the *Even* or *Odd paths* can be stored as a 6-bit word in memory. The use of memory, however, can be avoided if we determine each bit's outcome as an output of a combinational logic block with 6 inputs (i.e., the address bits). For example, this implementation is shown in **Fig. 8**.

Each of the 6 bits in the output word is evaluated as an output of the *Even* or *Odd* combinational block. Six multiplexers choose the results of the *Odd path* in the positive half of the clock cycle and the *Even path* in the negative half of the clock cycle. This parallel to serial conversion implements the upsampling. The 6-bit output word is fed to a digital-to-analog converter that generates the analog output.

The *Even* and *Odd paths* can have D flip-flops at their ends, so as to latch to the output. The clock applied to these D flip-flops can be delayed to compensate for the delay in the combinational blocks. The clock fed to the multiplexer select terminal is further delayed to compensate for the clock to output delay of the flip-flops at the output of *Odd* and *Even paths*.

Using the topology described in **Fig. 8**, a 13-tap raised cosine filter is designed for a roll-off factor of 0.3235 and an upsampling factor of 2. The simulated eye-diagram for a data rate of

3.8 Gbps is shown in **Fig. 10**. The signal spectrum before and after filtering is shown in **Fig. 11**. The filter includes some clock feedthrough, which may be avoided by using differential filters as explained above.

While exemplary embodiments of the present invention have been disclosed herein, it will be apparent to those skilled in the art that many modifications, additions, and deletions can be made therein without departing from the spirit and scope of the invention and its equivalents, as set forth in the following claims.

CLAIMS

What is claimed is:

1. A pulse shaping filter comprising:
a delay system comprising a digital delay chain;
a multiplier system comprising at least one multiplier adapted to multiply a signal from an input signal or the delay system by a predetermined non-zero coefficient, the multiplier system comprising a current reference branch and at least one current branch system coupled to the current reference; and
an adding system for summing each output of each multiplier of the multiplier system.
2. The pulse shaping filter of claim 1, the digital delay chain comprising a plurality of delays.
3. The pulse shaping filter of claim 2, the number of the plurality of delays dependent on a position of the last non-zero coefficient.
4. The pulse shaping filter of claim 1, the digital delay chain comprising a plurality of D-flipflops performing delays and obtaining a unit delay of half the symbol period by ANDing the delayed signals with CLK and CLK_bar signals.
5. The pulse shaping filter of claim 4, the current reference branch adapted to receive a biasing current and the current reference branch comprising:
a first PMOS transistor comprising a first PMOS source, a first PMOS gate, and a first PMOS drain;
a first NMOS transistor comprising a first NMOS transistor source, a first NMOS transistor gate, and a first NMOS transistor drain; and
a first NMOS switch comprising a first NMOS switch source, first NMOS switch gate, and a NMOS switch drain.

6. The pulse shaping filter of claim 5, the current reference branch further comprising:
a first transistor comprising a first source, a first drain, and a first gate,
wherein:
the biasing current is coupled to the first drain and the first gate of the first transistor,
the first source of the first transistor is coupled to a ground;
the first gate of the first transistor is further coupled to a first NMOS transistor gate of the NMOS transistor,
the first NMOS transistor gate of the first NMOS transistor is coupled to a gate node,
the first NMOS transistor source of the first NMOS transistor is coupled to the ground,
the first NMOS transistor drain of the first NMOS transistor is coupled to the NMOS switch source of the first NMOS switch,
the first NMOS switch gate of the first NMOS switch is coupled to a voltage supply,
the first NMOS switch drain of the first NMOS switch is coupled to the first PMOS drain and the first PMOS gate of the first PMOS transistor and a voltage (V_{bias}),
and
the first PMOS source of the first PMOS transistor is coupled to the voltage supply.
7. The pulse shaping filter of claim 5, the branch system coupled to the predetermined non-zero coefficient and comprising:
a second PMOS transistor comprising a second PMOS source, a second PMOS gate, and a PMOS drain;
a second NMOS transistor comprising a second NMOS transistor source, a second NMOS transistor gate, and a NMOS transistor drain; and

a second NMOS switch comprising a second NMOS switch source, second NMOS switch gate, and a second NMOS switch drain.

8. The pulse shaping filter of claim 7, the branch system further comprising:
a second transistor comprising a second source, a second gate, and a second drain,
9. The pulse shaping filter of claim 8, the number of the branch systems is dependent on a number of predetermined non-zero coefficients.
10. The pulse shaping filter of claim 9, the transistors of the branch system comprising quick charging and discharging transistors for speedy charging and discharging of nodes and enabling high speed operation.
11. The pulse shaping filter of claim 9, the adding system comprising an equal number of transistors as the number of predetermined non-zero coefficients.
12. The pulse shaping filter of claim 11, the adding system generating an output.

13. A pulse shaping filter operating in the digital domain comprising:
- a delay system comprising a plurality of D-flipflops, the number of the plurality of D-flipflops dependent on the desired number of taps;
 - a processing system comprising a lookup table based digital implementation created by splitting processing paths into two paths and evaluating outputs in the two paths in advance; and
 - an n-bit digital to analog converter receiving n-bits output from the processing system for providing an output.
14. The pulse shaping filter of claim 13, the lookup table processing outputs of the delay system is adapted to reduce the size of the lookup table from 2^m to $2^{(m-1)/2}$ for an m-tap pulse shaping filter.
15. The pulse shaping filter of claim 13, the processing system further comprising a dual-input MUX receiving the outputs of the lookup table and a clock signal for performing the upsampling.
16. The pulse shaping filter of claim 15, the dual-input MUX adapted to perform an upsampling by a factor of two.

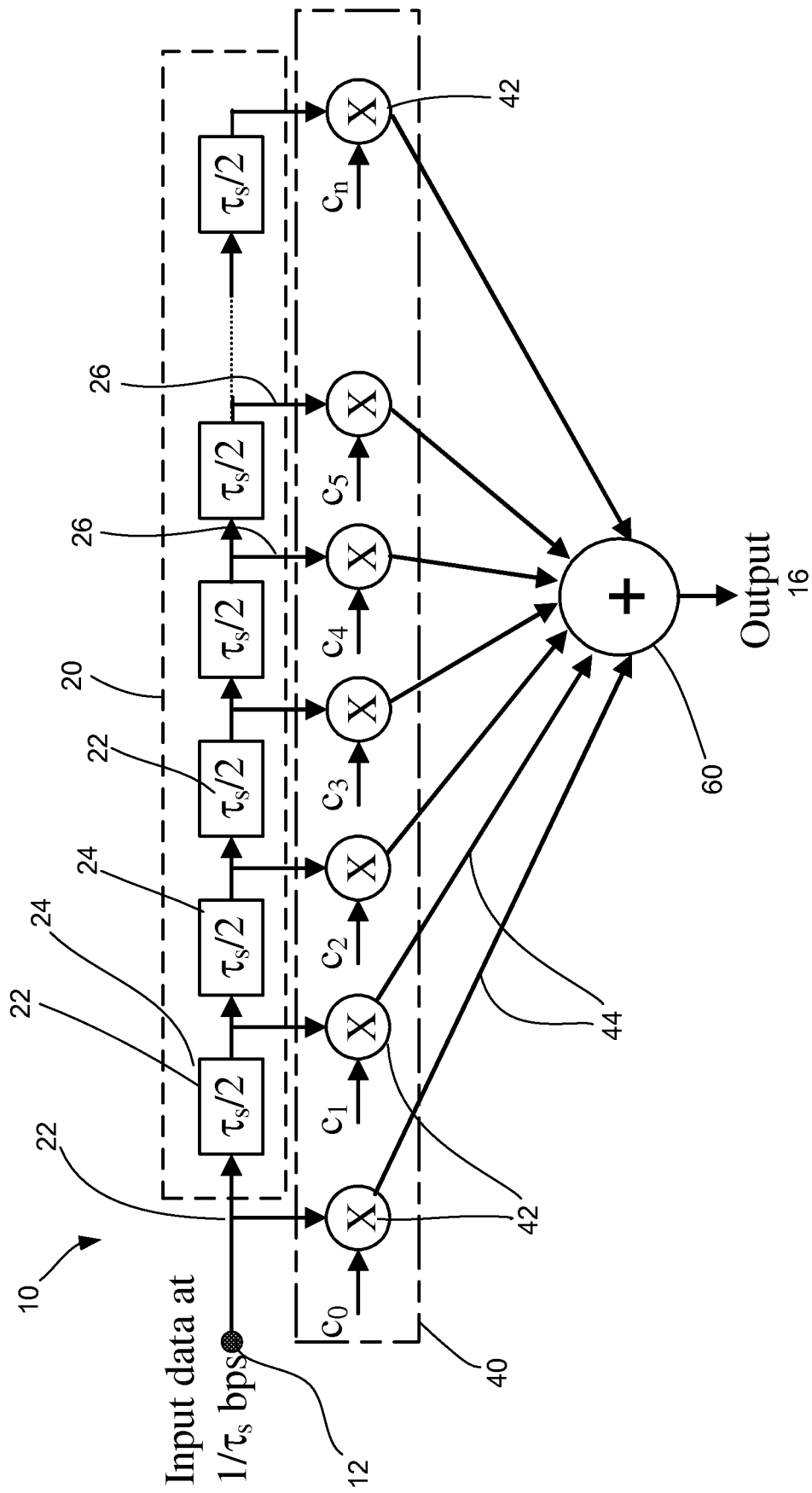


Fig. 1
Prior Art

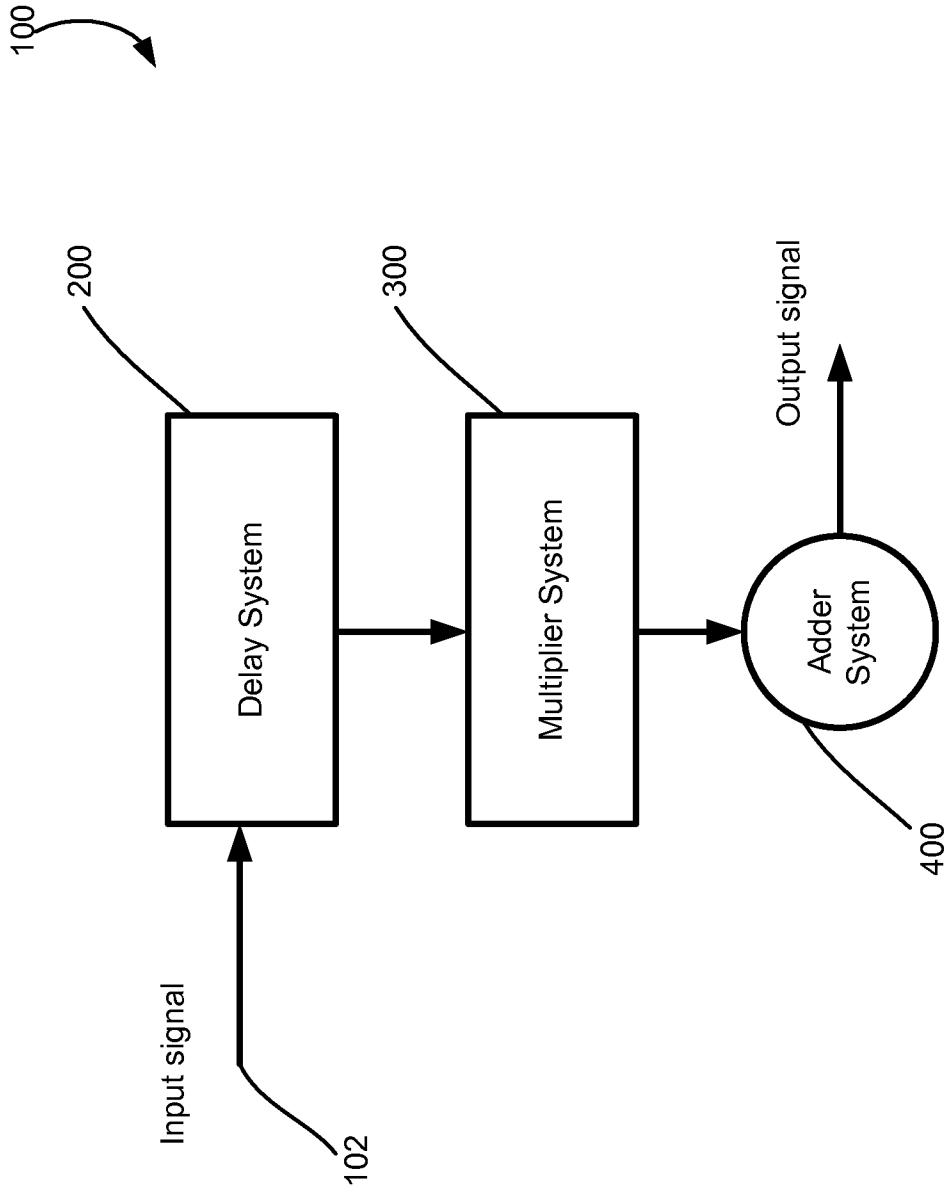


Fig. 2

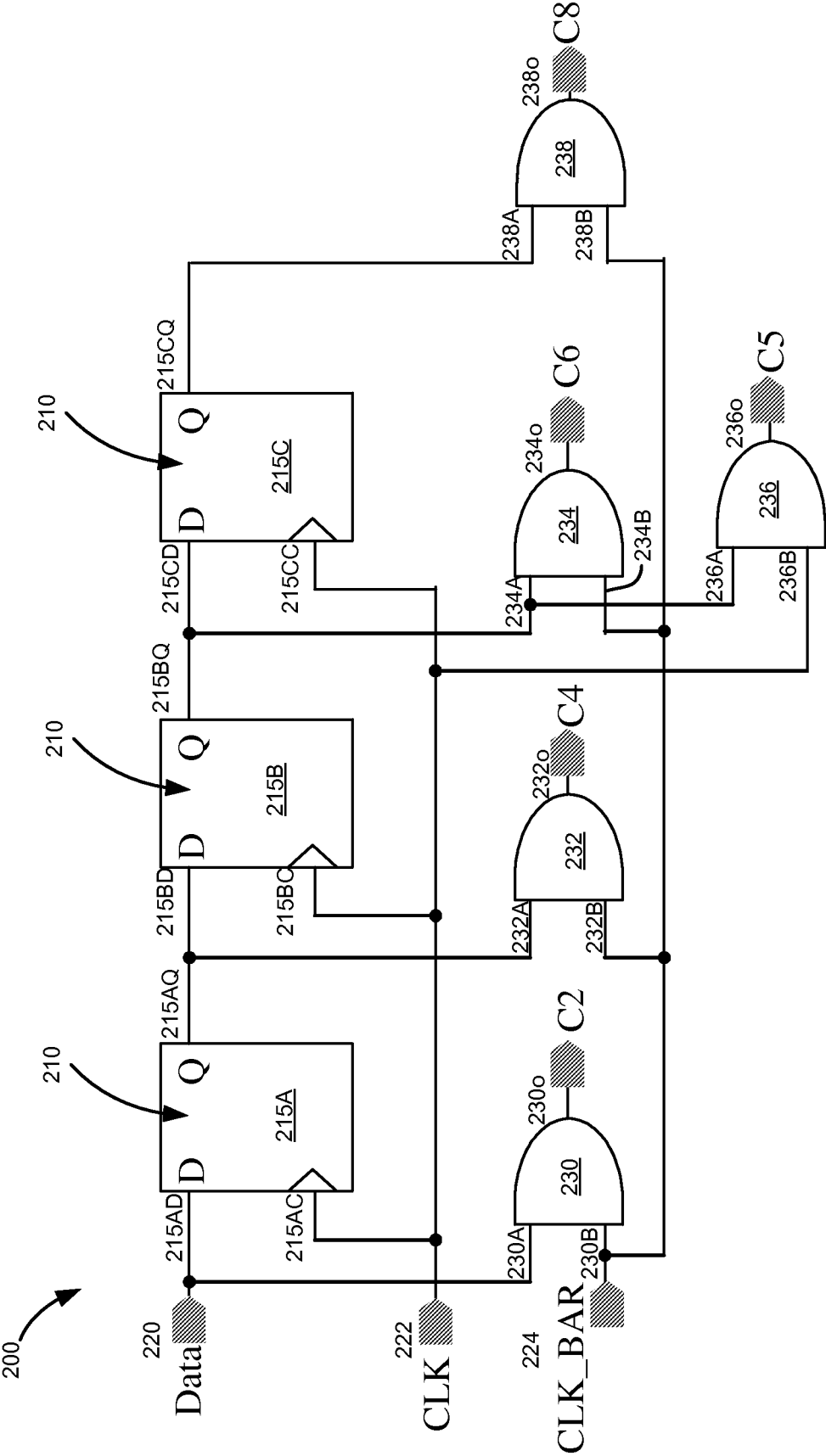


Fig. 3

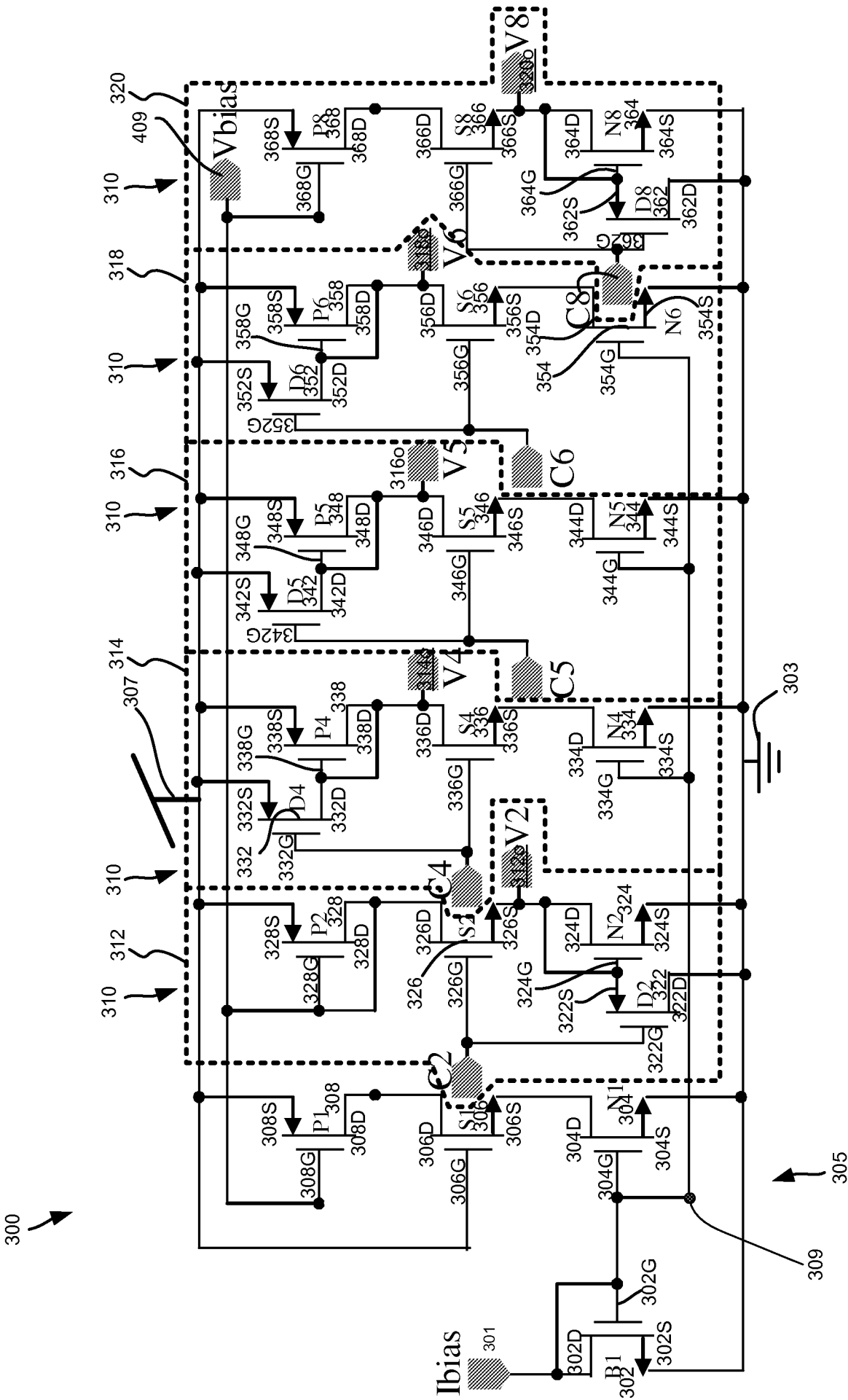
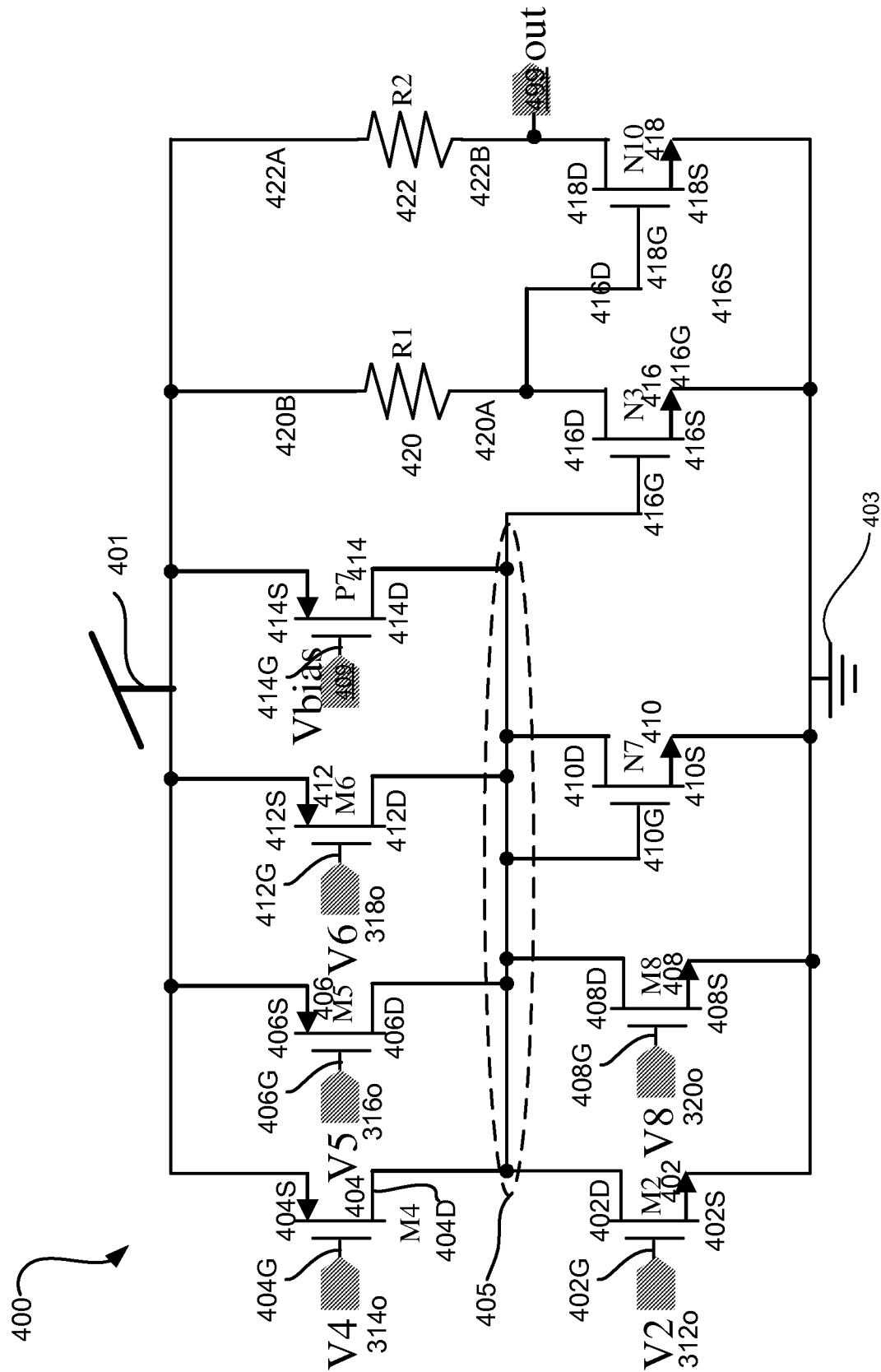


Fig. 4



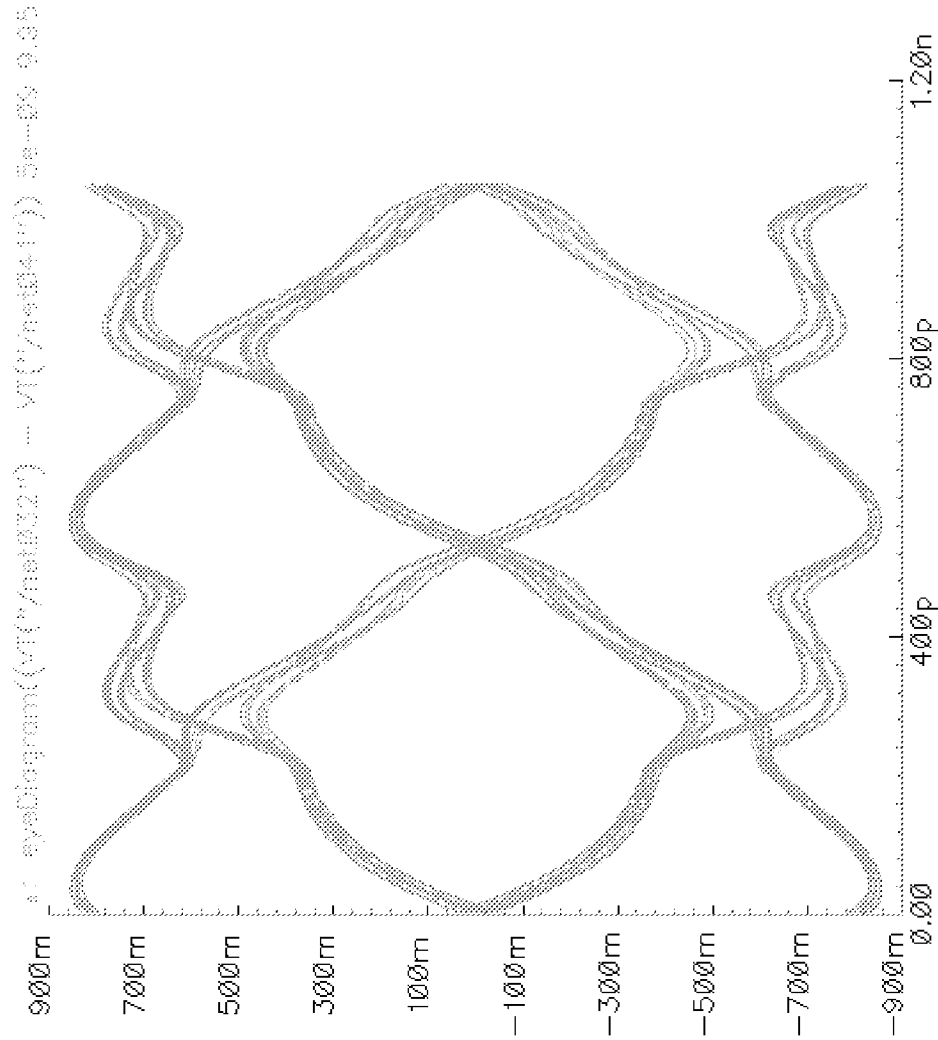


Fig. 6

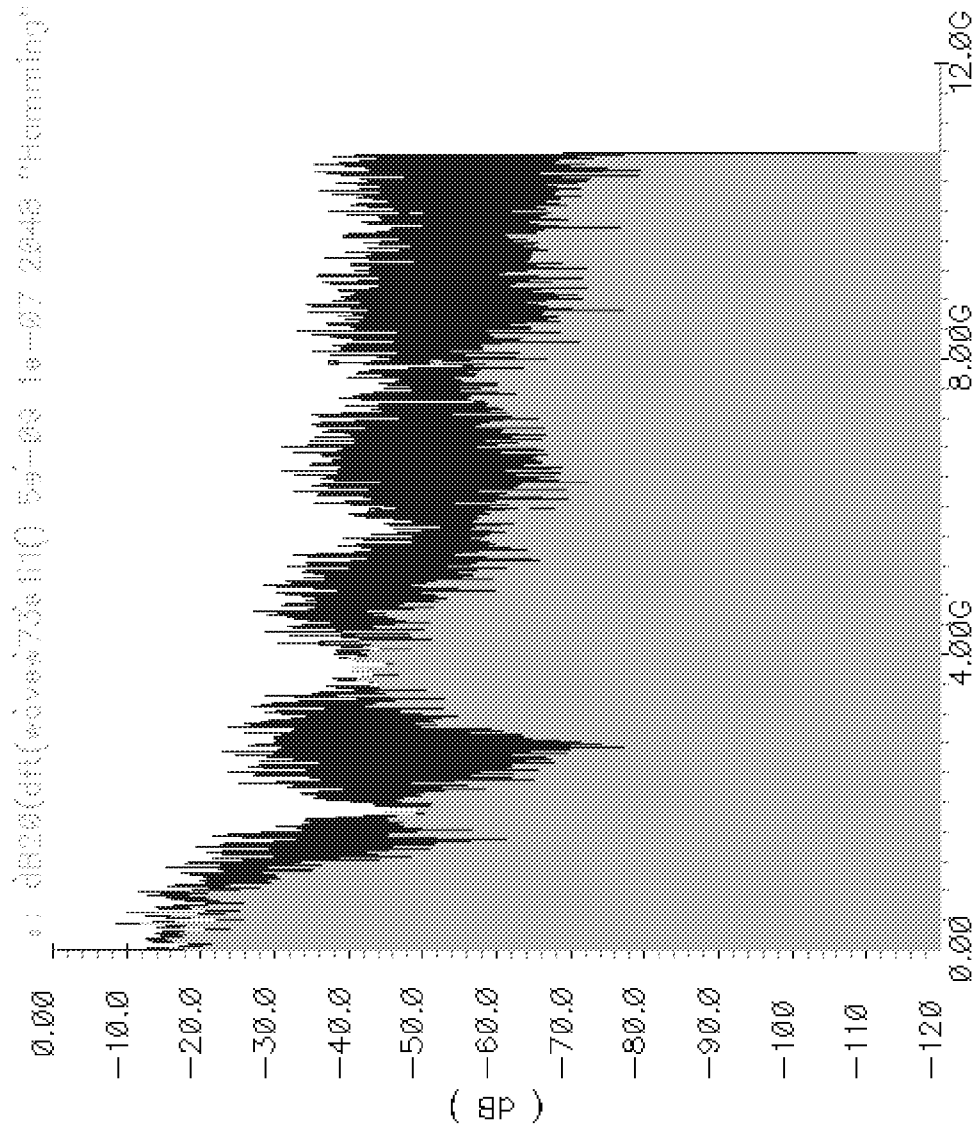


Fig. 7

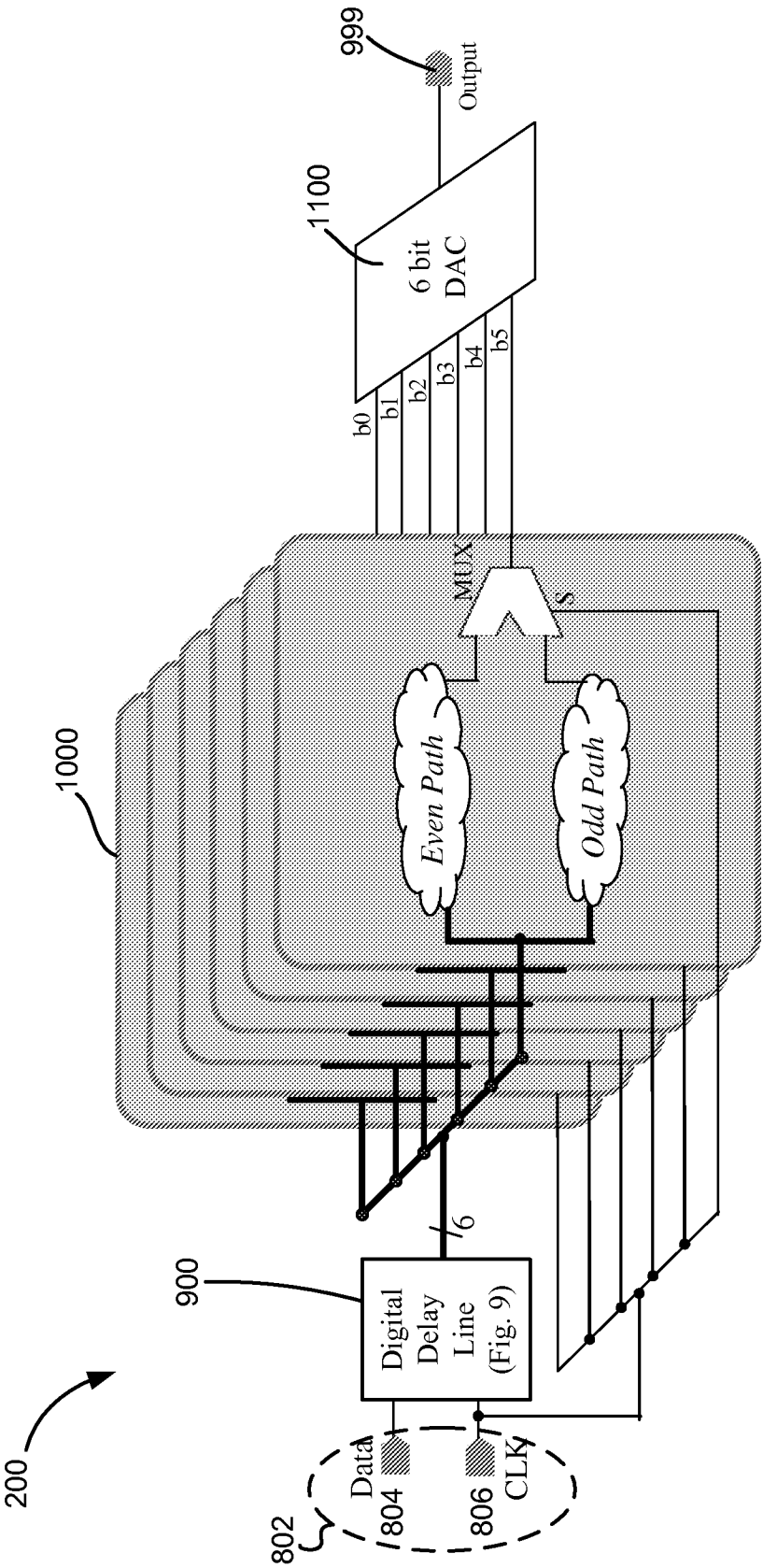


Fig. 8

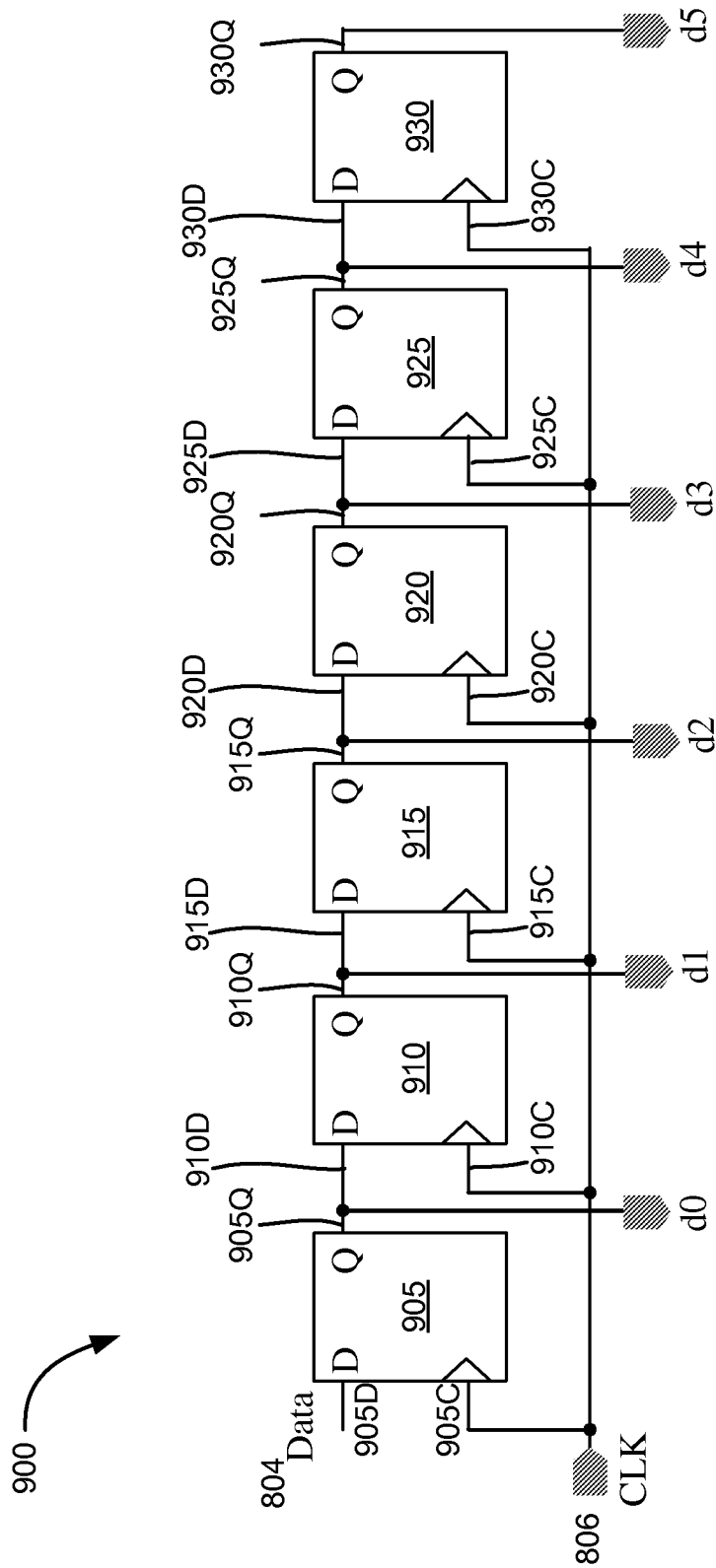


Fig. 9

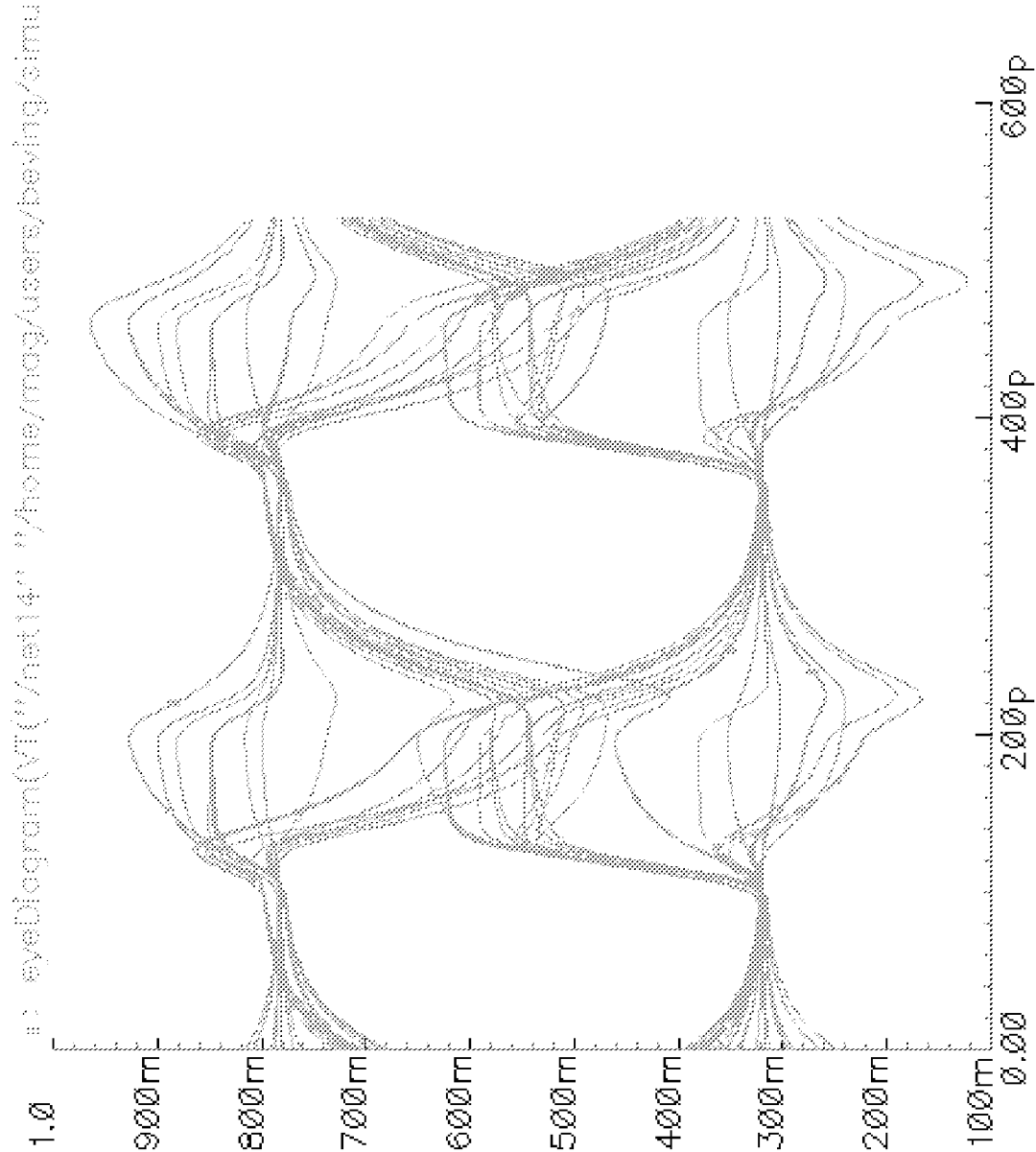


Fig. 10

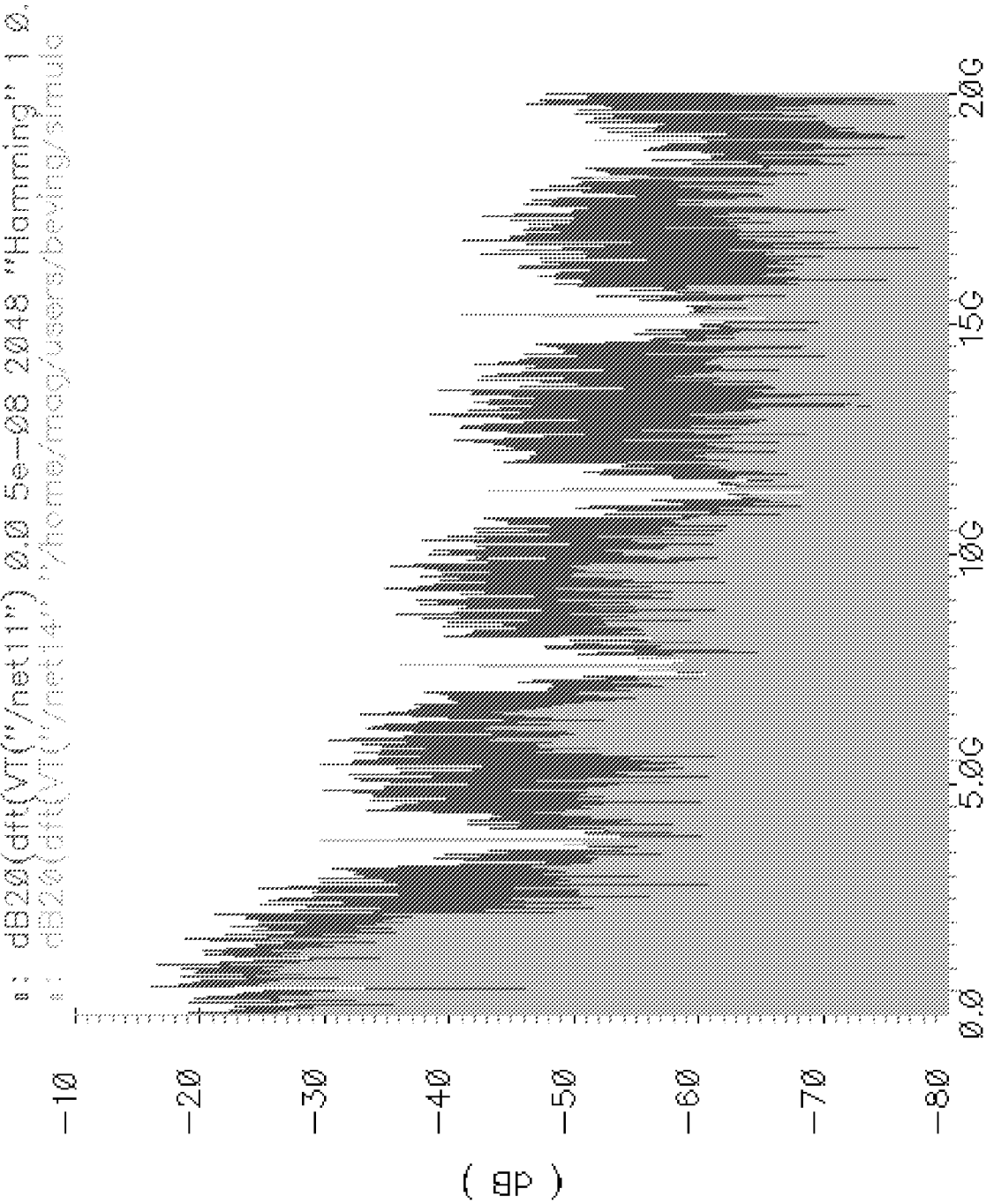


Fig. 11

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 08/85356

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H04N 7/12 (2009.01)

USPC - 375/240.29

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: 375/240.29

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

USPC: 375/240.29, 296; 327/1 (text search)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

PubWEST (USPT, PGPB, EPAB, JPAB), and Google Patent/Scholar

Search Terms Used: pulse shaping filter delay coefficient transistor nmos pmos drain branch adding subtract charging discharging clock CLK CLK_bar

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,910,960 A (Claydon et al.) 08 June 1999 (08.06.1999), entire document, especially; col 1, ln 10-30, col 2, ln 10-25, col 4, ln 15-50, col 5, ln 20-60, col 10, ln 1-15, col 12, ln 50-65, col 13, ln 25-65, col 15, ln 5-55, col 18, ln 15-50, col 19, ln 55-67, col 20, ln 25-65, col 21, ln 1-25, col 25, ln 35-55, col 26, ln 15-50, col 27, ln 15-67, col 28, ln 1-30, col 29, ln 1-65, col 32, ln 50-60, col 33, ln 20-35, col 34, ln 10-30, col 35, ln 1-30, Fig. 5, 6	1-3, 13-16 ----- 4-12
Y	US 2003/0231038 A1 (Koch, II et al.) 18 December 2003 (18.12.2003), entire document, especially; para [0030], [0032], [0033], Fig. 3, 5	4-12

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

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"P" document published prior to the international filing date but later than the priority date claimed

"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

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"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

"&" document member of the same patent family

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