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PROGRAMMABLE DELAY-LINE CIRCUIT WITH SINGLE DELAY ARRAY AND REAL-TIME CALIBRATION

Abstract

A programmable delay-line circuit is provided that includes a single ring oscillator that is calibrated continuously by a calibration logic circuit. A clock edge sampler samples an input clock responsive to a plurality of oscillator output signals from the ring oscillator to form a corresponding plurality of data output signals. A clock edge voter processes the data output signals to identify a first one of the oscillator output signals that samples an edge transition of the input clock. Based upon a desired delay, a decoder selects for a second one of the oscillator output signals to produce an output clock signal.

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Background/Summary

TECHNICAL FIELD

[0001] The present application relates generally to delay-line circuits, and more specifically to a programmable delay-line circuit with a single delay array and real-time calibration.

BACKGROUND

[0002] Programmable delay-line circuits have a wide variety of applications. For example, a dynamic random-access memory (DRAM) controller will typically include a programmable delay-line circuit. By adjusting the delay from the programmable delay-line circuit, the DRAM controller may delay a data strobe with respect to a memory clock signal so as to position the data strobe in the center of the data eye. A programmable delay-line circuit is also used within delay-locked loop circuits. Although programmable delay-line circuits are thus quite useful, they are subject to process, voltage, and temperature variations that affect their accuracy.

SUMMARY

[0003] In accordance with an aspect of the disclosure, a delay-line circuit for delaying an input clock signal is provided that includes: a ring oscillator including a plurality of delay cells, the ring oscillator configured to produce oscillator output signals; a clock edge sampler configured to generate data output signals, the clock edge sampler including a plurality of flip-flops corresponding to the plurality of delay cells on a one-to-one basis, each flip-flop being configured to latch the input clock signal responsive to an oscillator output signal from a corresponding delay cell to produce a corresponding data output signal; and a delay output decoder configured to process the data output signals to select a first one of the oscillator output signals to form an output clock signal.

[0004] In accordance with another aspect of the disclosure, a method is provided that includes: generating a corresponding oscillator output signal in each delay cell in a plurality of delay cells arranged to form a ring oscillator; sampling an input clock signal responsive to each oscillator output signal to form a plurality of data output signals; processing the data output signals to identify a first one of the oscillator output signals as sampling an edge transition of the input clock signal; and outputting a second one of the oscillator output signals as an output clock signal.

[0005] Finally, in accordance with yet another aspect of the disclosure, a delay-line circuit is provided that includes: a single ring oscillator configured to produce a plurality of oscillator output signals; a clock edge sampler configured to sample an input clock signal according to the plurality of oscillator output signals to provide a plurality of data output signals; and a decoder configured to select one of the oscillator output signals as an output clock signal responsive to a processing of the plurality of data output signals.

[0006] These and other advantageous features may be better appreciated through the following detailed description.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. 1 illustrates a programmable delay-line circuit in accordance with an aspect of the disclosure.

[0008] FIG. 2 is a diagram of some waveforms from a programmable delay-line circuit in accordance with an aspect of the disclosure.

[0009] FIG. 3 is a truth table for a clock edge voter in accordance with an aspect of the disclosure.

[0010] FIG. 4 illustrates an example delay circuit for the ring oscillator of the programmable delay-line circuit of FIG. 1 in accordance with an aspect of the disclosure.

[0011] FIG. 5 is a flowchart of a method of operation for a programmable delay-line circuit in accordance with an aspect of the disclosure.

[0012] FIG. 6 illustrates some example electronic systems including a programmable delay-line circuit in accordance with an aspect of the disclosure.

[0013] Implementations of the present disclosure and their advantages are best understood by referring to the detailed description that follows. It should be appreciated that like reference numerals are used to identify like elements illustrated in one or more of the figures.

DETAILED DESCRIPTION

[0014] A variety of approaches have been developed to address the process, voltage, and temperature variations that affect the accuracy of a delay from a programmable delay-line circuit. In one approach, a programmable delay-line circuit may include a pair of delay arrays in a master-slave relationship. A master delay array in the pair is continually calibrated with respect to a reference clock signal. A slave delay array in the pair generates the delayed output signal within a delay-locked loop based upon a phase-locked loop (PLL) output signal from a PLL that includes the master delay array. Although the delayed output signal is thus continually calibrated, there is a static delay error between the master and slave delay arrays that cannot be calibrated out. In addition, the delayed output signal was subject to a relatively long settling time and thus hindered instantaneous delay tracking ability. The analog design of the PLL is also not easy to port from one process node to another.

[0015] In another architecture, two delay arrays alternate between a delay mode and a calibration mode such that while one of the delay arrays is in the calibration mode, the remaining delay array is in the delay mode to drive the delayed output signal. However, the switching between the two delay arrays to drive the delayed output signal causes delay uncertainty. In addition, the calibration may have a limited ability to track voltage and temperature variations.

[0016] A calibrated programmable delay-line circuit is provided that uses a single delay array (which is also denoted herein as a ring oscillator) and thus does not suffer from mismatches between delay arrays. In addition, the calibration is always on and thus may readily track process, voltage, and temperature variations. Moreover, the delayed output signal is available from an initial clock cycle and thus does not suffer from any extended settling time. An example programmable delay-line circuit **100** is shown in FIG. 1. A glitch-free ring oscillator **105** includes a plurality of n delay circuits (e.g., 4, 8, 16, and so on) arranged in a ring from a zeroth delay circuit to an $(n-1)$ th delay circuit. Each delay circuit is also denoted herein as a delay unit. As known in the ring oscillator arts, each delay circuit functions to delay an output signal from a preceding delay circuit in the ring oscillator **105**. For example, the zeroth delay circuit delays an output signal from the $(n-1)$ th delay circuit to drive a delayed output signal to a first delay circuit. In turn, the first delay circuit drives a delayed output signal to a second delay circuit (not illustrated). In this fashion, each subsequent delay circuit in the ring oscillator **105** delays an output signal from the preceding delay circuit. For example, the $(n-1)$ th delay circuit delays an output signal from an $(n-2)$ th delay circuit.

[0017] The output signal from each delay circuit is also denoted herein as an oscillator output signal. The ring oscillator **105** thus produces a plurality of n oscillator output signals that all share the same frequency but each having a unique phase. Since each oscillator output signal has the same frequency, the oscillator output signals all have the same oscillation period. The number n of delay circuits determines a corresponding number n of oscillator clock signal phases from the ring oscillator **105**. For example, the zeroth delay circuit may be deemed to produce a corresponding oscillation output signal ($\text{Ph}<0>$) having a clock edge transition (either a rising edge from ground to a power supply voltage or a falling edge from the power supply voltage to ground) that is synchronous with a beginning of the oscillation period. The first delay circuit would then produce a corresponding oscillation output signal ($\text{Ph}<1>$) that transitions at $(1/n)$ th of the oscillation period after the beginning of the oscillation period. More generally, an i th delay circuit produces a corresponding oscillation output signal that transitions at (i/n) th of the oscillation period after the

beginning of the oscillation period, where i represents the integer order of the delay circuit in the progression from 0 to $n-1$.

[0018] The plurality of n oscillation output signals from the n delay circuits in the ring oscillator **105** are sampled by a clock edge sampler **110** with respect to an edge transition (e.g., a rising-edge from ground to a power supply voltage) of an input clock signal (clk_in). Each oscillation output signal is sampled by a corresponding memory element such as a data (D) type flip-flop. For example, a zeroth flip-flop (FF) samples the zeroth oscillation output signal $Ph<0>$ from the zeroth delay circuit. Similarly, a first flip-flop samples the first oscillation output signal $Ph<1>$ from the first delay circuit. In the same fashion, an $(n-2)$ th flip-flop samples an $(n-2)$ th oscillation output signal $Ph<n-2>$ from the $(n-2)$ th delay circuit. Finally, an $(n-1)$ th flip-flop samples an $(n-1)$ th oscillation output signal from the $(n-1)$ th delay circuit.

[0019] Each flip-flop of the n flip-flops in the clock edge sampler **110** receives the input clock signal at its data (D) input and is clocked by the corresponding oscillation output signal. The zeroth flip-flop will thus register the input clock signal at a rising edge of the zeroth oscillation output signal $Ph<0>$. A data output signal $Dout<0>$ from the zeroth flip-flop thus captures the binary value (either 0 or 1) of the input clock signal at the rising edge of the zeroth oscillation output signal $Ph<0>$. Similarly, the first flip-flop registers the input clock signal at a rising edge of the first oscillation output signal $Ph<1>$. A data output signal $Dout<1>$ from the first flip-flop thus captures the binary value of the input clock signal at the rising edge of the first oscillation output signal $Ph<1>$. The $(n-2)$ th flip-flop registers the input clock signal at the rising edge of the $(n-2)$ th oscillation output signal $Ph<n-2>$. A data output signal $Dout<n-2>$ from the $(n-2)$ th flip-flop thus captures the binary value of the input clock signal at the rising edge of the $(n-2)$ th oscillation output signal $Ph<n-2>$. Finally, the $(n-1)$ th flip-flop registers the input clock signal at a rising edge of the $(n-1)$ th oscillation output signal $Ph<n-1>$. A data output signal $Dout<n-1>$ from the $(n-1)$ th flip-flop thus captures the binary value of the input clock signal at the rising edge of the $(n-1)$ th oscillation output signal $Ph<n-1>$.

[0020] Following the rising edge of the input clock signal, the input clock signal will stay charged to the power supply voltage depending upon the duty cycle of the input clock signal. Depending upon the duty cycle, a corresponding number of the data output signals will have a binary one value following the rising edge of the input clock signal. However, since the clock edge sampling by the n flip-flops in the clock edge sampler **110** is asynchronous with respect to the input clock signal, it is possible that a given data output signal could have a binary one or zero value due to a glitch. A delay output decoder **120** thus includes a clock edge voter **125** that examines a trio of consecutive ones of the data output signals. For example, the clock edge voter **125** processes the zeroth data output signal $Dout<0>$, the first data output signal $Dout<1>$, and a second data output signal $Dout<2>$. Similarly, the clock edge voter **125** processes the first data output signal $Dout<1>$, the second data output signal $Dout<2>$, and a third data output signal $Dout<3>$, and so on. This processing of a trio of data output signals is advantageous with respect to preventing a glitch from being interpreted as a detection of the rising edge of the input clock signal.

[0021] To process these triples of consecutive data output signals, the clock edge voter **125** receives the n data output signals $Dout<n-1:0>$. In addition, the clock edge voter **125** receives a one-sample delayed version of the n data output signals $Dout<n-2:0>$, $Dout<n-1>$ and also receives a two-sample delayed version of the n data output signals $Dout<n-3:0>$, $Dout<n-1:n-2>$. A current data output signal from the n data output signals $Dout<n-1:0>$ may be denoted as a B signal. Similarly, a one-sample preceding data output signal from the current data output signal may be denoted as an A signal. Finally, a one-sample delayed output signal from the current data output signal may be denoted as a C signal. The clock edge voter **125** thus processes the A, B, and C signals to decide whether the current data output signal has sampled the rising edge of the input clock signal.

[0022] In one implementation, the clock edge voter **125** may include a first logic gate such as a first NAND gate **135** that NANDS the A and B data output signals and also include a second logic gate

such as a second NAND gate **140** that NANDs the B and C data output signals. A third NAND gate **145** NANDs an output signal from the NAND gate **135**, an output signal from the NAND gate **140**, and its inverted output signal as inverted by an inverter **150** to produce a current data vote output signal that represents a vote as to whether the current data output signal B has sampled a rising edge of the input clock signal. The clock edge voter **125** produces n votes corresponding to the n data output signals. For example, when the current data output signal is the second data output signal Dout<2>, the clock edge voter **125** also examines the first data output signal Dout<1> and a third data output signal Dout<3> to determine whether to set a binary value for a second data vote output signal D_vot<2> (not illustrated). More generally, the clock edge voter **125** examines an ith data output signal Dout<i>, an (i-1)th data output signal Dout<i-1>, and an (i+1)th data output signal Dout<i+1> to determine a binary value of an ith data vote output signal D_vot<i>, where i represents the integer order of the current data output signal in the progression from 0 to n-1.

[0023] The clock edge voter **125** sets the ith data vote output signal D_vot<i> to a binary one if the ith data output signal Dout<i> and at least one of the data output signals Dout<i-1> and Dout<i+1> also equals a binary one. Suppose that the ith data output signal Dout<i> is a binary zero only because of a clock edge sampling glitch due to the lack of synchrony between the ith oscillator output signal Ph<i> and the clock input signal and/or due to instability of the ith flip-flop. In that case, the preceding data output signal Dout<i-1> and the subsequent data output signal Dout<i+1> will both be a binary one. The clock edge voter **125** would then set the ith data vote output signal D_vot<i> to a binary one despite the glitch at the ith data output signal Dout<i>. With the rising edge of the input clock signal detected by the corresponding ith data vote output signal D_vot<i>, a decoder **130** can then select from the oscillator output signals Ph<n-1:0> according to a desired delay. For example, suppose that the desired delay equals (m/n)th of the oscillation period, where m is a positive integer less than n. The decoder **130** may then output the oscillator output signal Ph<i+m> as the delayed output clock signal.

[0024] Some example operating waveforms for the clock edge sampler **110** and the delay output decoder **120** are shown in FIG. 2 for an implementation in which n (the number of oscillation output signals from the ring oscillator **105**) equals sixteen. The oscillation output signals thus range from a zeroth oscillation output signal Ph<0> to a fifteenth oscillation output signal Ph<15>. The clock input signal (clk_in) has a rising edge slightly before the second oscillation output signal Ph<2>. The zeroth data output signal Dout<0> and the first data output signal Dout<1> will both be binary zeroes. A first data vote output signal D_vot<1> (not illustrated) will also be a binary zero since both the first data output signal Dout<1> and its preceding data output signal Dout<0> are both binary zeroes. The second data output signal Dout<2> may be a binary zero, a binary one, or a glitch depending upon the stability of the second flip-flop. But the third data output signal Dout<3> will be a binary one as the rising edge of the third oscillation output signal Ph<3> occurs well after the rising edge of the clock input signal. Should the second data output signal Dout<2> be sampled as a binary one, the second data vote output signal D_vot<2> will be a binary one since both the second data output signal Dout<2> and the third data output signal Dout<3> are binary ones. But if the second data output signal Dout<2> is a binary zero or a glitch, the second data vote output signal D_vot<2> will be a binary zero.

[0025] An example truth table for the clock edge voter **125** is as shown in FIG. 3. The data vote output signal is denoted as "OUTPUT" whereas the binary values of the A, B, and C data output signals is denoted as "INPUT." It is only when at least two of the A, B, and C data output signals are binary ones that the OUTPUT signal is a binary one. Otherwise, the OUTPUT signal is a binary zero.

[0026] Suppose that the second data vote output signal D_vot<2> is a binary one. The decoder **130** (FIG. 1) will then select for the oscillation output signal Ph<m+2>, where m is the desired integer delay as discussed earlier. Should m equal 11, the decoder **130** would output the thirteenth oscillation output signal Ph<13> to form the delayed output clock signal (clk_out). The selected

oscillation output signal to form the delayed output clock signal may also be denoted herein as a first one of the oscillation output signals.

[0027] Referring again to FIG. 1, note that the oscillation period and frequency of the ring oscillator **105** is subject to process, voltage, and temperature variations. For example, the oscillation frequency will decrease as the temperature falls, which increases the oscillation period and thus increases the delay between consecutive ones of the oscillation output signals. To calibrate out these process, voltage, and temperature variations, a calibration logic circuit such as a counter-based calibration finite-state machine (FSM) circuit **115** receives one of the oscillation output signals as an oscillator clock signal (osc_clk). The counter-based FSM circuit **115** also receives a stable clock signal such as a crystal oscillator clock signal Tcxo. The counter-based FSM circuit **115** may count according to cycles of the crystal oscillator signal to establish a count for the oscillator period or frequency of the ring oscillator **105**. Should this count be too low, the counter-based FSM circuit **115** adjusts a tuning signal Txdelay<m: 0> to increase the oscillation frequency of the ring oscillator **105**, where the tuning signal Txdelay has a resolution of m+1 bits, m being a positive integer. Alternatively, if the count is too high, the counter-based FSM circuit **115** adjusts the tuning signal Txdelay to decrease the oscillation frequency of the counter-based FSM circuit **115**.

[0028] To respond to tuning signal Txdelay, each delay circuit of the ring oscillator may be implemented as shown for an example delay circuit **400** of FIG. 4. The delay circuit **400** includes a plurality of delay cells arranged in series that depend upon the resolution of the tuning signal Txdelay. For example, suppose that the tuning signal Txdelay is a 5-bit tuning signal. This 5-bit tuning signal may be converted into a thirty-two-bit thermometer-encoded enable signal ranging from a zeroth enable signal en<0> that controls a zeroth delay cell **405** to a thirty-first enable signal en<31> that controls a thirty-first delay cell **410**. The oscillator input signal to the zeroth delay cell **405** is received by a NAND gate **490** that also receives the power supply voltage. An output signal from the NAND gate **490** is processed by a NAND gate **420** that also NANDs an output signal from a latch formed by a cross-coupled pair of NAND gates **435** and **430**. A NAND gate **425** NANDs an output signal from the NAND gate **420** with an output signal from a first delay cell (not illustrated) to form the oscillator output signal for the delay circuit **400**. The NAND gate **430** also NANDs the output signal from the first delay cell. An AND gate **440** ANDs the oscillator output signal to form a clocking signal for a D-type flip-flop in each of the delay cells. For example, the first delay cell **405** includes a D-type flip-flop **415** that latches the zeroth enable signal en<0> responsive to the clocking by the oscillator output signal to drive an input of the NAND gate **435**.

[0029] Depending upon the corresponding enable signal, each delay cell contributes to the delay of the oscillator output signal. For example, the thirty-first delay cell includes a D-type flip-flop **450** that latches the thirty-first enable signal en<31> when clocked by the oscillator output signal to drive an input of a NAND gate **470** that is cross-coupled with a NAND gate **465** to form a latch. A NAND gate **455** NANDs an output signal from a NAND gate **445** and the NAND gate **470**. The NAND gate **455** NANDs an output signal from the thirtieth delay cell (not illustrated) and the Q output signal from the D-type flip-flop (not illustrated) in the thirtieth delay cell. A NAND gate **460** NANDs an output signal from the NAND gate **455**. The output signal from the NAND gate **445** is also processed serially through three NAND gates **475**, **480**, and **485** that are configured as inverters to drive the NAND gate **465** and the NAND gate **460**. An output signal from the NAND gate **460** is received by the equivalent of NAND gate **430** (not illustrated) in the thirtieth delay cell.

[0030] It will be appreciated that other architectures may be used to form each delay circuit in the ring oscillator **105**. In that regard, the NAND gates in the delay cells of FIG. 4 may be replaced by other types of logic gates. Regardless of how the delay cells are formed, note that the programmable delay-line circuit **100** uses just one ring oscillator **105** that is advantageously continuously calibrated. There is thus no mismatch issue between delay arrays as discussed previously nor is there any settling time required.

[0031] A method of operation for a programmable delay-line as disclosed herein will now be discussed with respect to the flowchart of FIG. 5. The method includes an act **500** of generating a corresponding oscillator output signal in each delay cell in a plurality of delay cells arranged to form a ring oscillator. The generation of the plurality of n oscillator output signals $Ph_{<n-1:0>}$ in the ring oscillator **105** is an example of act **500**. The method also includes an act **505** of sampling an input clock signal responsive to each oscillator output signal to form a plurality of data output signals. The sampling of the input clock clk_in by the clock edge sampler **110** is an example of act **505**. In addition, the method includes an act **510** of processing the data output signals to identify a first one of the oscillator output signals as sampling an edge transition of the input clock signal. The processing of the data output signals as discussed with regard to the clock edge voter **125** is an example of act **510**. Finally, the method includes an act **515** of outputting a second one of the oscillator output signals as an output clock signal. The selection from the oscillator output signals $Ph_{<n-1:0>}$ as discussed with respect to the decoder **130** is an example of act **515**.

[0032] A programmable delay-line circuit as disclosed herein may be incorporated in a wide variety of electronic systems. For example, as shown in FIG. 6, a cellular telephone **600**, a laptop computer **605**, and a tablet PC **610** may all include a programmable delay-line circuit in accordance with the disclosure. Other exemplary electronic systems such as an earbud, a music player, a video player, a communication device, and a personal computer may also be configured with a programmable delay-line circuit constructed in accordance with the disclosure.

[0033] The disclosure will now be summarized through the following example clauses:

Clause 1. A delay-line circuit for delaying an input clock signal, comprising: [0034] a ring oscillator including a plurality of delay cells, the ring oscillator configured to produce oscillator output signals; [0035] a clock edge sampler configured to generate data output signals, the clock edge sampler including a plurality of flip-flops corresponding to the plurality of delay cells on a one-to-one basis, each flip-flop being configured to latch the input clock signal responsive to an oscillator output signal from a corresponding delay cell to produce a corresponding data output signal; and [0036] a delay output decoder configured to process the data output signals to select a first one of the oscillator output signals to form an output clock signal.

Clause 2. The delay-line circuit of clause 1, further comprising: [0037] a calibration logic circuit configured to calibrate an oscillation frequency of the ring oscillator.

Clause 3. The delay-line circuit of clause 2, wherein the calibration logic circuit is configured to count responsive to cycles of a crystal oscillator signal to calibrate the oscillation frequency of the ring oscillator.

Clause 4. The delay-line circuit of any of clauses 1-3, wherein each flip-flop in the plurality of flip-flops comprises a data (D) type flip-flop.

Clause 5. The delay-line circuit of any of clauses 1-4, wherein the delay output decoder is configured to process three consecutive ones of the data output signals to identify a second one of the oscillator output signals as sampling a transition edge of the input clock signal, and wherein the first one of the oscillator output signals is delayed by an integer number of the oscillator output signals with respect to the second one of the oscillator output signals.

Clause 6. The delay-line circuit of clause 5, wherein the delay output decoder is further configured to process the three consecutive ones of the data output signals through an identification of whether at least two of the three consecutive data output signals have a same binary value.

Clause 7. The delay-line circuit of any of clauses 1-6, wherein the ring oscillator includes a plurality of n delay circuits, wherein n is a multiple of two, and wherein the plurality of flip-flops comprises a plurality of n flip-flops.

Clause 8. The delay-line circuit of clause 7, wherein n equals sixteen.

Clause 9. The delay-line circuit of clause 5, wherein the delay output decoder includes a clock voter circuit having a first logic gate configured to process a first data output signal and a second data output signal from the three consecutive data output signals, and having a second logic gate

configured to process the second data output signal and a third data output signal from the three consecutive data output signals.

Clause 10. The delay-line circuit of clause 9, wherein the first logic gate comprises a first NAND gate, and wherein the second logic gate comprises a second NAND gate.

Clause 11. The delay-line circuit of clause 10, wherein the clock voter circuit further comprises: [0038] a third NAND gate; and [0039] an inverter configured to invert an output signal from the third NAND gate, and wherein the third NAND gate is configured to NAND an output signal from each of the first NAND gate, the second NAND gate, and the inverter.

Clause 12. A method, comprising: [0040] generating a corresponding oscillator output signal in each delay cell in a plurality of delay cells arranged to form a ring oscillator; [0041] sampling an input clock signal responsive to each oscillator output signal to form a plurality of data output signals; [0042] processing the plurality of data output signals to identify a first one of the oscillator output signals as sampling an edge transition of the input clock signal; and [0043] outputting a second one of the oscillator output signals as an output clock signal.

Clause 13. The method of clause 12, further comprising: [0044] calibrating an oscillation frequency of the ring oscillator.

Clause 14. The method of clause 13, wherein calibrating the oscillation frequency of the ring oscillator comprises adjusting the oscillation frequency of the ring oscillator with respect to an oscillation frequency of a crystal oscillator signal.

Clause 15. The method of any of clauses 12-14, wherein processing the data output signals comprises identifying whether a trio of consecutive ones of the data output signals includes at least two data output signals having a binary one value.

Clause 16. A delay-line circuit, comprising: [0045] a single ring oscillator configured to produce a plurality of oscillator output signals; [0046] a clock edge sampler configured to sample an input clock signal according to the plurality of oscillator output signals to provide a plurality of data output signals; and [0047] a decoder configured to select one of the oscillator output signals as an output clock signal responsive to a processing of the plurality of data output signals.

Clause 17. The delay-line circuit of clause 16, further comprising: [0048] a calibration logic circuit configured to calibrate an oscillation frequency of the single ring oscillator during an operation of the single ring oscillator.

Clause 18. The delay-line circuit of clause 17, wherein the calibration logic circuit is further configured to count responsive to a crystal oscillator signal to form a count and to calibrate the oscillation frequency responsive to the count.

Clause 19. The delay-line circuit of any of clauses 16-18, wherein the clock edge sampler comprises a plurality of flip-flops.

Clause 20. The delay-line circuit of clause 19, wherein the single ring oscillator comprises a plurality of delay circuits corresponding on a one-to-one basis with the plurality of flip-flops. [0049] As those of some skill in this art will by now appreciate and depending on the particular application at hand, many modifications, substitutions and variations can be made in and to the materials, apparatus, configurations and methods of use of the devices of the present disclosure without departing from the scope thereof as defined by the appended claims. In light of this, the scope of the present disclosure should not be limited to that of the particular implementations illustrated and described herein, as they are merely by way of some examples thereof, but rather, should be fully commensurate with that of the claims appended hereafter and their functional equivalents.

Claims

1. A delay-line circuit for delaying an input clock signal, comprising: a ring oscillator including a plurality of delay cells, the ring oscillator configured to produce oscillator output signals; a clock

edge sampler configured to generate data output signals, the clock edge sampler including a plurality of flip-flops corresponding to the plurality of delay cells on a one-to-one basis, each flip-flop being configured to latch the input clock signal responsive to an oscillator output signal from a corresponding delay cell to produce a corresponding data output signal; and a delay output decoder configured to process the data output signals to select a first one of the oscillator output signals to form an output clock signal.

2. The delay-line circuit of claim 1, further comprising: a calibration logic circuit configured to calibrate an oscillation frequency of the ring oscillator.

3. The delay-line circuit of claim 2, wherein the calibration logic circuit is configured to count responsive to cycles of a crystal oscillator signal to calibrate the oscillation frequency of the ring oscillator.

4. The delay-line circuit of claim 1, wherein each flip-flop in the plurality of flip-flops comprises a data (D) type flip-flop.

5. The delay-line circuit of claim 1, wherein the delay output decoder is configured to process three consecutive ones of the data output signals to identify a second one of the oscillator output signals as sampling a transition edge of the input clock signal, and wherein the first one of the oscillator output signals is delayed by an integer number of the oscillator output signals with respect to the second one of the oscillator output signals.

6. The delay-line circuit of claim 5, wherein the delay output decoder is further configured to process the three consecutive ones of the data output signals through an identification of whether at least two of the three consecutive data output signals have a same binary value.

7. The delay-line circuit of claim 1, wherein the ring oscillator includes a plurality of n delay circuits, wherein n is a multiple of two, and wherein the plurality of flip-flops comprises a plurality of n flip-flops.

8. The delay-line circuit of claim 7, wherein n equals sixteen.

9. The delay-line circuit of claim 5, wherein the delay output decoder includes a clock voter circuit having a first logic gate configured to process a first data output signal and a second data output signal from the three consecutive data output signals and having a second logic gate configured to process the second data output signal and a third data output signal from the three consecutive data output signals.

10. The delay-line circuit of claim 9, wherein the first logic gate comprises a first NAND gate, and wherein the second logic gate comprises a second NAND gate.

11. The delay-line circuit of claim 10, wherein the clock voter circuit further comprises: a third NAND gate; and an inverter configured to invert an output signal from the third NAND gate, and wherein the third NAND gate is configured to NAND an output signal from each of the first NAND gate, the second NAND gate, and the inverter.

12. A method, comprising: generating a corresponding oscillator output signal in each delay cell in a plurality of delay cells arranged to form a ring oscillator; sampling an input clock signal responsive to each oscillator output signal to form a plurality of data output signals; processing the plurality of data output signals to identify a first one of the oscillator output signals as sampling an edge transition of the input clock signal; and outputting a second one of the oscillator output signals as an output clock signal.

13. The method of claim 12, further comprising: calibrating an oscillation frequency of the ring oscillator.

14. The method of claim 13, wherein calibrating the oscillation frequency of the ring oscillator comprises adjusting the oscillation frequency of the ring oscillator with respect to an oscillation frequency of a crystal oscillator signal.

15. The method of claim 12, wherein processing the data output signals comprises identifying whether a trio of consecutive ones of the data output signals includes at least two data output signals having a binary one value.

- 16.** A delay-line circuit, comprising: a single ring oscillator configured to produce a plurality of oscillator output signals; a clock edge sampler configured to sample an input clock signal according to the plurality of oscillator output signals to provide a plurality of data output signals; and a decoder configured to select one of the oscillator output signals as an output clock signal responsive to a processing of the plurality of data output signals.
- 17.** The delay-line circuit of claim 16, further comprising: a calibration logic circuit configured to calibrate an oscillation frequency of the single ring oscillator during an operation of the single ring oscillator.
- 18.** The delay-line circuit of claim 17, wherein the calibration logic circuit is further configured to count responsive to a crystal oscillator signal to form a count and to calibrate the oscillation frequency responsive to the count.
- 19.** The delay-line circuit of claim 16, wherein the clock edge sampler comprises a plurality of flip-flops.
- 20.** The delay-line circuit of claim 19, wherein the single ring oscillator comprises a plurality of delay circuits corresponding on a one-to-one basis with the plurality of flip-flops.
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