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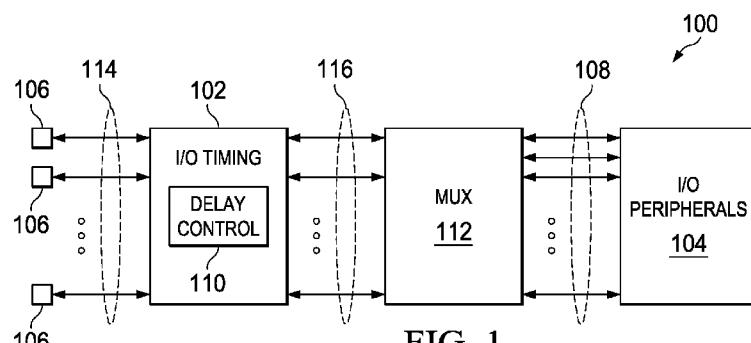


FIG. 1

(57) Abstract: In described examples, an integrated circuit (IC) (100) includes input/output (I/O) terminals (106) through which signals pass into or out of the IC (100). Also, the IC (100) includes an I/O timing module (102) configured to add propagation delay to signals passing between the I/O terminals (106) and I/O subsystems (104) of the IC (100). The I/O timing module (102) includes delay elements associated with each of the I/O terminals (106), a control register associated with each of the I/O terminals (106), a memory, and I/O delay control logic. The control register is coupled to each of the delay elements associated with the I/O terminal (106). The memory is encoded with delay information. The I/O delay control logic is configured to initialize the propagation delay associated with each of the I/O terminals (106) by selecting which of the delay elements are to be applied to produce the propagation delay based on the delay information stored in the memory.

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METHOD AND SYSTEM FOR CONTROLLING CIRCUIT INPUT-OUTPUT TIMING

[0001] This relates in general to integrated circuits, and in particular to a method and system for controlling circuit input-output timing.

BACKGROUND

[0002] The process of modifying an integrated circuit (IC) to meet pre-established timing requirements is referred to as “timing closure.” Timing closure can be a challenging task for IC designs, because the timing margins shift with changes to process/environment parameters (such as process corners). Accordingly, an optimal implementation for one process corner can fail to meet the timing requirements at another process corner. Numerous place and route and/or other design process iterations may be required to produce a design that meets the pre-established timing requirements (such as setup and hold times) for the IC across process corners. Accordingly, timing closure can result in an objectionable increase in the time and cost associated with designing an IC.

SUMMARY

[0003] In described examples, an integrated circuit (IC) includes input/output (I/O) terminals through which signals pass into or out of the IC. Also, the IC includes an I/O timing module configured to add propagation delay to signals passing between the I/O terminals and I/O subsystems of the IC. The I/O timing module includes delay elements associated with each of the I/O terminals, a control register associated with each of the I/O terminals, a memory, and I/O delay control logic. The control register is coupled to each of the delay elements associated with the I/O terminal. The memory is encoded with delay information. The I/O delay control logic is configured to initialize the propagation delay associated with each of the I/O terminals by selecting which of the delay elements are to be applied to produce the propagation delay based on the delay information stored in the memory.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] FIG. 1 shows a block diagram of an integrated circuit (IC) including input/output (I/O) terminal propagation delay control.

[0005] FIG. 2 shows a block diagram of an I/O timing control module that controls timing at IC I/O terminals.

[0006] FIG. 3 shows a block diagram of a delay calibration controller that measures delays of delay elements applied to control timing at IC I/O terminals.

[0007] FIG. 4 shows a block diagram of a delay controller that sets timing for IC I/O terminals.

[0008] FIG. 5 shows a flow diagram for a method of controlling propagation delay associated with IC I/O terminals.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

[0009] A method and system for optimizing timing closure by controlling the propagation delay of signals routed to input/output (I/O) terminals of an integrated circuit (IC) are disclosed herein. Ensuring that circuitry (associated with the I/O terminals) meets predetermined timing requirements is a substantial part of the process of timing closure for the IC. Similar ICs may include similar peripheral devices, but timing closure for I/O signals associated with the peripheral devices may require time consuming iterative static timing analysis using different parameters and adjustment of circuit placement and routing. Furthermore, conventional timing closure processes are strained when multiplexing signals to/from an I/O terminal using I/O pin/signal selection, because additional effort may be required to ensure that each signal meets I/O timing requirements.

[0010] Embodiments of the integrated circuits disclosed herein include I/O timing circuitry that simplifies the process of timing closure for signals routed to/from I/O terminals of an IC. Accordingly, the example embodiments are suitable for reducing cost and time in designing an IC. The I/O timing circuitry disclosed herein provides programmable delay to I/O signals, thereby allowing the timing of I/O signals to be controlled without the substantial iterative timing analysis and place and route of conventional ICs. Embodiments of the I/O timing circuitry measure the delay provided by delay elements of the I/O timing circuitry under operational conditions, and adaptively apply the delay elements to provide a preprogrammed propagation delay for each I/O signal to meet the pre-established timing requirements of the IC.

[0011] FIG. 1 shows a block diagram of an IC 100 including I/O terminal propagation delay control in accordance with various embodiments. The IC 100 includes I/O terminals 106, an I/O timing control module 102, an I/O signal multiplexer 112, and I/O peripherals 104. The IC 100 may also include other circuitry and systems that are not shown in FIG. 1 for clarity. The I/O terminals 106 are signal transfer structures through which the circuitry of the IC 100 is coupled to circuitry external to the IC 100. The I/O terminals 106 may include conductive pins, pads, and other elements.

[0012] The I/O peripherals 104 are subsystems that include various devices that drive signals to or receive signals from one or more of the I/O terminals 106. Examples of devices that may be included in the I/O peripherals include general purpose I/O logic, universal asynchronous/synchronous receive/transmit logic, serial peripheral interface logic, inter-IC (I²C) logic, timers, audio ports, network adapters, memory controllers, and video controllers. Signals 108 are routed between the I/O peripherals 104 and the multiplexer 112.

[0013] The multiplexer 112 provides selectable routing of signals between the I/O terminals 112 and the I/O peripherals 104. For example, the multiplexer 112 may allow one of sixteen different signals 108 generated by the I/O peripherals 104 to be selectively routed to each I/O terminal 106. Similarly, the multiplexer 112 may allow one of sixteen different I/O terminals 106 to be connected to an input of an I/O peripheral 104. Signals may be selected for routing to/from the I/O terminals 106 during operation of the IC 100. The number of signals that can be selectively routed between each of the I/O terminals 106 and outputs of the I/O peripherals, and/or between the I/O terminals 106 and each input of the I/O peripherals 104 may vary in different embodiments of multiplexer 112. Signals 116 are routed between the multiplexer 112 and the I/O timing control module 102.

[0014] The I/O timing control module 102 controls the propagation delay of signals 114 routed to/from the I/O terminals 106 through the I/O timing control module 102 from/to the I/O peripherals 104. The I/O timing control module 102 includes a delay controller 110. The delay controller 110 determines how a predetermined amount of propagation delay specific to each I/O signal passing through the I/O timing control module 102 is to be generated and applied. By applying an appropriate propagation delay to each I/O signal, the I/O timing control module 102 simplifies timing closure with respect to signals routed to/from the I/O terminals 106.

[0015] In some embodiments of the IC 100, at least some of the peripheral devices of the I/O peripherals 104 may be included in a “hardened” circuitry component, in conjunction with the I/O timing control module 102 and the multiplexer 112. In such embodiments, the routing between the peripheral devices and the I/O timing control module 102 is fixed, which simplifies the determination of propagation delays applied by the I/O timing control module 102, and further simplifies the process of timing closure with respect to the signals routed between the I/O terminals 106 and the peripheral devices. Some peripheral devices of the I/O peripherals 104, such as complex peripheral devices (including memory controllers and/or video controllers), may be

located outside such a hardened component. The I/O timing control module 102 also simplifies timing closure with respect to such peripherals.

[0016] FIG. 2 shows a block diagram of the I/O timing control module 102. The I/O timing control module 102 includes delay elements 202, a delay interface 204, delay calibration logic 206, the delay controller 110, and delay storage 210. The delay storage 210 includes a storage device (such as a non-volatile memory, FLASH storage, or read-only-memory storage). Delay values 220 are stored in the delay storage 210. The delay values 220 specify the propagation delay to be applied to each I/O signal that can pass through the I/O timing control module 102 to/from an I/O terminal 106. The delay values 220 may be determined during design of the IC 100 by analysis of delays across various corners. The delay storage 210 may include storage location sufficient to store a number of delay values equivalent to the number of I/O terminals 106 times the number of signals routable to each I/O terminal 106 via the multiplexer 112.

[0017] The delay elements 202 include a set of delay elements or delay lines corresponding to each of the I/O terminals 106. The signals 114 associated with the I/O terminals 106, and the signals 116 associated with the multiplexer 112, are connected to the delay elements 202 for insertion of propagation delay. The delay elements 202 are selectable and/or programmable to obtain a propagation delay in accordance with each of the delay values stored in the delay storage 210. The set of delay elements 202 associated with each I/O terminal 106 includes coarse delay elements 218 and fine delay elements 216. Each of the coarse delay elements 218 provides a substantially longer delay than each of the fine delay elements 216. For example, a coarse delay element may provide about 1 nanosecond of delay, and fine delay element may provide less than 100 picoseconds of delay. In some embodiments, the set of delay elements 202 corresponding to an I/O terminal 106 may include twenty-two (22) coarse delay elements 218 and twenty-two (22) fine delay elements 216. Other embodiments may include a different number of fine and/or coarse delay elements per I/O terminal 106.

[0018] The delay calibration controller 206 measures the delay provided by the coarse delay elements 218 and the delay provided by the fine delay elements 216 during operation of the IC 100. The delay controller 110 applies the measured coarse and fine delay values to determine how the delay elements 202 should be applied to achieve a propagation delay value for a given I/O signal, as specified by a delay value 220 retrieved from the delay storage 210. Accordingly, the calibration controller 206 allows the delay controller 110 to account for changes in propagation

delay of the delay elements 202 caused by environmental conditions, such as process, temperature, and/or voltage.

[0019] The delay controller 110 controls the delay elements 202 via the delay interface 204. The delay interface 204 includes logic (such as a control register corresponding to each I/O terminal 106) that generates control signals for selecting which of the coarse and fine delay elements 218, 216 are to be applied to generate a given signal propagation delay. For example, the delay interface 204 may include a control register (coupled to each delay element 202), which provides signals for selecting which of delay elements 202 is to be used for effectuating a needed propagation delay. The delay interface 204 also provides an interface to a bus 212 that allows circuitry external to the I/O timing control module 102 to select which of the delay elements 202 are applied to delay an I/O signal, and to communicate with the delay controller 110. Accordingly, via the delay interface 204, external circuitry can override or adjust propagation delay values set by the delay controller 110, and initiate various functions of the I/O timing control module 102.

[0020] The delay controller 110 can change the propagation delay associated with an I/O terminal 106, based on a change in the signal routed to the I/O terminal 106. The signals 214 notify the delay controller 110 of changes in the identity, source, and/or destination of signals passing through the I/O timing control module 102. Changes in signal identity, source, and/or destination may be effectuated via the multiplexer 112. After the delay controller 110 is notified of such a signal change, via the signals 214, the delay controller 110 can retrieve a delay value for the new signal from the delay storage 210, determine how the delay elements 202 are to be applied to effectuate the retrieved delay value, and select the appropriate delay elements to effectuate the propagation delay via the delay interface 204. Accordingly, the I/O timing control module 102 can vary the propagation delay applied in conjunction with an I/O terminal 106 in association with runtime changes in the identity of the signal routed to the I/O terminal 106.

[0021] FIG. 3 shows a block diagram of the delay calibration controller 206. The delay calibration controller 206 measure delays of delay elements 202 applied to control timing at I/O terminals 106. The delay calibration controller 206 includes delay counters 302 and 316, reference counters 304 and 318, and delay calculation logic 306. The delay calibration controller 206 measures the delay of both coarse and fine delay elements 218, 216.

[0022] To measure the delay provided by the coarse delay elements 218, the calibration logic 206 (or the delay controller 110 to facilitate delay measurement) selects a predetermined number of

coarse delay elements (such as 88 elements), arranged in series. The selected set of coarse delay elements 218 is arranged as a ring oscillator, and the oscillation output 308 of the ring oscillator is connected to the delay counter 302.

[0023] The reference counter 304 is incremented by a reference clock signal 310 of known frequency. The count outputs of the delay counter 302 and the reference counter 304 are provided to the delay calculation logic 306. The delay calculation logic 306 can enable counting by the delay counter 302 and the reference counter 304 at a given time (such as a same time) to initiate delay measurement, and disable counting by both counters 302, 304 at a later time (such as when either counter 302, 304 reaches a maximum count value or a predetermined count value).

[0024] Based on the known period of the reference clock 310 and the ratio of the final count values of the delay and reference counters 302, 304, the delay calculation logic 306 determines the period of the ring oscillator output 308 and the total delay provided by the serially arranged coarse delay elements 218. The delay calculation logic 306 divides the total delay by the number of coarse delay elements 218 in the ring oscillator to determine the delay provided by each individual coarse delay element 218 under operating conditions. The delay calculation logic 314 provides the measured delay to the delay controller 110 for use in determining which of the delay elements 202 is to be applied to effectuate a propagation delay. The measured coarse delay per element (CDPE) may be calculated as:

$$CDPE = \frac{(RefCnt * RefClkPeriod)}{(2 * CrsDlyCnt * NumCrsElements)}$$

where: *RefCnt* is the final count value of the reference counter 304; *RefClkPeriod* is the known period of the reference clock signal 310; *CrsDlyCnt* is the final count value of the delay counter 302; and *NumCrsElements* is the number coarse delay elements in the coarse delay ring oscillator.

[0025] The delay calibration controller 206 measures the delay of fine delay elements 216 in a manner similar to that described for the coarse delay elements 218. When measuring the delay of the fine delay elements 216, a number of fine delay elements 216 that is substantially larger than number of coarse delay elements 218 applied in coarse element calibration may be used. For example, two-hundred sixty-four (264) fine delay elements may be sequentially arranged to form a ring oscillator generating oscillation signal 320. The reference counter 318 and the delay counter 316 are incremented by reference clock 310 and fine delay ring oscillator output clock 320 respectively, until halted by the delay calculation logic 306. The final count values of the counters

316, 318 are used for computing the measured fine delay per element (*FDPE*) as:

$$FDPE = \frac{(RefCnt * RefClkPeriod)}{(2 * FineDlyCnt * NumFineElements)}$$

where: *RefCnt* is the final count value of the reference counter 318; *RefClkPeriod* is the period of the reference clock signal 310; *FineDlyCnt* is the final count value of the delay counter 316; and *NumFineElements* is the number fine delay elements in the fine delay ring oscillator.

[0026] The delay calibration logic 206 may be triggered to measure the delays provided by the elements 216, 218 at device initialization (such as power on reset time). In some embodiments of the I/O timing control module 102, the delay calibration logic 206 may be triggered via the signals 214 to initiate delay measurement. For example, execution of software instructions may trigger recalibration based on an identified change in operating conditions, such as voltage or temperature.

[0027] FIG. 4 shows a block diagram of the delay controller 110. The delay controller 110 includes delay adjustment logic 402 that determines which of the set of delay elements 202 corresponding to an I/O terminal 106 to apply to an I/O signal to provide a propagation delay specified by a delay value 220 retrieved from delay storage 210. The delay adjustment logic 402 applies the measured delays 314 provided by the delay calibration controller 206, and predicted/expected delay values 404, which may be delay values predicted by design for the coarse and fine delay elements 218, 216 to determine which delay elements 202 should be applied to generate the propagation delay specified by the delay value 220.

[0028] Because the interconnect and other delays on different paths (such as clock and data paths) can vary differently across operating conditions, application of a fixed propagation delay via the delay elements 202 may result in timing violations for some process/temperature/voltage combinations. Embodiments of the I/O timing control module 102 overcome this difficulty by specifying propagation delay in two parts, which are: process invariant (agnostic) delay and process variant (gnostic) delay.

[0029] The delay value 220 retrieved from delay storage 210 includes a process agnostic delay value 406 and a process gnostic delay value 412 that conjunctively specify the propagation delay for a corresponding I/O signal I/O terminal combination. The process gnostic delay value 412 specifies a portion of the delay value 220 that scales from max corner to min corner of the IC 100, in the same manner as other circuitry of the IC 100. The process gnostic delay value 412 includes a coarse delay value 414 and a fine delay value 416. The coarse delay value 414 and fine delay

value 416 may respectively specify a number coarse delay elements 218 and a number of fine delay elements 216.

[0030] The process agnostic delay value 406 specifies a portion of the delay value 220 that remains the same across corners of the IC 100, such as delay that is fixed with respect to process and operating conditions. The process agnostic delay value 406 also includes a coarse delay value 408 and a fine delay value 410. The coarse delay value 408 and fine delay value 410 may respectively specify a number coarse delay elements 218 and a number of fine delay elements 216. However, the delay specified by values 408, 410 is process invariant, and consequently does not change with operational conditions.

[0031] The delay controller 110 may compute the total coarse delay (*CrsDly*) to be applied to a given I/O terminal for a given I/O signal as:

$$CrsDly = ACrsDly * PredCrsDly + GCrsDly * CDPE$$

where: *ACrsDly* is a number of process agnostic coarse delay elements (e.g. coarse value 408); *PredCrsDly* is predicted or expected delay (404) of a coarse delay element; *GCrsDly* is a number of gnostic coarse delay elements (e.g. coarse value 414); and *CDPE* is measured delay (314) per coarse delay element.

[0032] Having computed the total coarse delay (*CrsDly*), the delay adjustment logic 402 determines the number of coarse delay elements 218 to apply as

$$CrsElements = CrsDly / CDPE .$$

[0033] Similarly, the delay adjustment logic 402 computes the total fine delay as:

$$FineDly = AFineDly * PredFineDly + GFineDly * FDPE$$

where: *AFineDly* is a number of process agnostic fine delay elements (e.g. fine value 410); *PredFineDly* is predicted or expected delay (404) of a fine delay element; *GFineDly* is a number of process gnostic fine delay elements (e.g. fine value 416); and *FDPE* is measured delay (314) per fine delay element.

[0034] The delay adjustment logic 402 computes the number of fine delay elements 218 to apply in conjunction with *CrsElements* as:

$$FineElements = FineDly / FDPE .$$

[0035] The total delay implemented by the delay adjustment logic 402 for the delay value 220 is:

$$TotalDly = CrsDly + FineDly ,$$

where the process agnostic portion of the specified delay does not vary with process and operating conditions, because the number of delay elements applied to provide the process agnostic delay varies based on the measured coarse and fine delay values 314. Accordingly, embodiments account for process invariant delays (such as metal delays) and process variant delays (such as component delays).

[0036] FIG. 5 shows a flow diagram for a method of controlling propagation delay associated with IC I/O terminals 106 in accordance with various embodiments. In block 502, the IC 100 is initialized. For example, the IC 100 may be performing operations associated with a power on reset. The delay calibration controller 206 measures the delays of the coarse delay elements 218 and the fine delay elements 216 under operating conditions during the initialization of the IC.

[0037] In block 504, the delay controller 110 accesses the delay storage 210 and retrieves from the delay storage 210 delay values 220. The delay values 220 specify the propagation delay to be applied to signal routing for each of the I/O terminals 106. Each of the delay values 220 specifies, for a signal routed to an I/O terminal 106, process invariant and process variant portions of the propagation delay for both coarse delay elements 218 and fine delay elements 216.

[0038] In block 506, the delay controller 110 computes the total coarse delay and the total fine delay to be applied to each signal routed to an I/O terminal 106. For a given signal, the total coarse delay is the sum of the coarse process invariant delay and the coarse process variant delay computed for the signal. The total fine delay is the sum of the fine process invariant delay and the fine process variant delay computed for the signal. The process invariant delays are computed as a product of a nominal or planned coarse/fine delay element delay value and the number of coarse/fine delay elements specified in the coarse/fine process invariant portion of the delay value 220. The process variant delays are computed as a product of a measured coarse/fine delay element delay value and the number of coarse/fine delay elements specified in the coarse/fine process variant portion of the delay value 220.

[0039] In block 508, the delay controller 110 selects which of the coarse delay elements 218 and which of the fine delay elements 216 are to be applied to provide the propagation delay specified by the delay value 220 for routing to an I/O terminal 106. The delay controller 110 may identify a number of coarse delay elements 218 to be applied based on the computed total coarse delay and the measured delay of a coarse delay element 218. The delay controller 110 may identify a number of fine delay elements 216 to be applied based on the computed total fine delay and the

measured delay of a fine delay element 216. The delay controller 110 writes information specifying the number of coarse delay elements 218 and the number of fine delay elements 216 to be applied to a control register that provides selection signals to the delay elements 202 corresponding to the I/O terminal 106. For example, one selection signal may be provided to each delay element 202.

[0040] In block 510, the delay controller 110 receives an indication of a change in signal routing to an I/O terminal 510. For example, the signal routed to the I/O terminal 106 may be changed via the multiplexer 112. The indication may result from assertion of a signal 214 by circuitry external to the I/O timing control module 102. In response to the indication of a change in signal routing, the delay controller 110 retrieves, from the delay storage 210, a delay value 220 corresponding to the new signal. The delay controller 110 computes delays for the delay value 220 as described for block 506, and selects delay elements to implement the delay as described for block 508.

[0041] In block 512, the delay calibration controller 206 is triggered to measure the delays of the coarse delay elements 218 and the fine delay elements 216. The triggering may result from assertion of a signal 214 by circuitry external to the I/O timing control module 102. In response to the triggering, the delay calibration controller 206 measures the delays of the coarse delay elements 218 and the fine delay elements 216 as described for block 502.

[0042] In block 514, the delay controller 110 is triggered to retrieve delay values 220 from the delay storage 210 and update the propagation delays implemented for I/O terminals 106. The triggering may result from assertion of a signal 214 by circuitry external to the I/O timing control module 102. In response to the triggering, the delay controller 110 performs the operations described for blocks 504-508.

[0043] Accordingly, in at least one embodiment, a method includes routing signals passing to or from I/O terminals of an IC through an I/O timing module of the IC. Propagation delay is added to the signals in the I/O timing module. Delay elements of the I/O timing module are selected, by the I/O timing module, to apply to each signal and provide the propagation delay based on an identity of the signal and delay information stored in the I/O timing module for the signal.

[0044] In a further embodiment, an IC includes I/O terminals and an I/O timing module. The I/O terminals are configured to pass signals into or out of the IC. The I/O timing module is configured to add propagation delay to the signals, and includes arrays of delay elements, propagation delay value storage, a calibration controller, and a delay controller. One of the arrays

of delay elements corresponds to each of the I/O terminals. The propagation delay value storage stores a propagation delay value for each of the signals. The calibration controller is configured to measure the propagation delay provided by the delay elements. The delay controller is configured to select, for each of the signals, based on the measured propagation delay of the delay elements, which of the delay elements to apply to provide the propagation delay specified by the propagation delay value.

[0045] Modifications are possible in the described embodiments, and other embodiments are possible, within the scope of the claims.

CLAIMS

What is claimed is:

1. An integrated circuit (IC), comprising:
 - a plurality of input/output (I/O) terminals through which signals pass into or out of the IC; and
 - an I/O timing module configured to add propagation delay to signals passing between the I/O terminals and I/O subsystems of the IC, the I/O timing module including: a plurality of delay elements associated with each of the I/O terminals; a control register associated with each of the I/O terminals and coupled to each of the delay elements associated with the I/O terminal; a memory encoded with delay information; and I/O delay control logic configured to initialize the propagation delay associated with each of the I/O terminals by selecting which of the delay elements are to be applied to produce the propagation delay based on the delay information stored in the memory.
2. The IC of claim 1, wherein, for each of the I/O terminals, the I/O delay control logic is configured to: retrieve the delay information from the memory; and determine which of the delay elements to enable in combination to produce the propagation delay.
3. The IC of claim 1, wherein the plurality of delay elements include: a plurality of coarse delay elements; and a plurality of fine delay elements; wherein the fine delay elements are configured to provide smaller delay than the coarse delay elements.
4. The IC of claim 3, wherein the I/O timing module includes delay calibration logic configured to measure a first delay value for each of the coarse delay elements, and a second delay value for each of the fine delay elements.
5. The IC of claim 4, wherein the I/O delay control logic is configured to initialize the propagation delay associated with each of the I/O terminals based on the first delay value and the second delay value.
6. The IC of claim 1, wherein the I/O timing module includes an I/O multiplexer configured to selectively route one of a plurality of signals to an I/O terminal; and wherein the I/O delay control logic is configured to change the propagation delay associated with the I/O terminal responsive to the I/O multiplexer changing which of the signals is routed to the I/O terminal, and based on the signal to be routed to the I/O terminal.
7. The IC of claim 1, wherein the I/O timing module includes a delay control interface

configured to allow circuitry external to the I/O timing module to set the propagation delay associated with each of the I/O terminals by writing a delay information value to the control register associated with each of the I/O terminals.

8. The IC of claim 1, wherein the delay information includes a process gnostic coarse delay value, a process gnostic fine delay value, a process agnostic coarse delay value, and a process agnostic fine delay value.

9. The IC of claim 8, wherein the I/O delay control logic is configured to compute the propagation delay, for an I/O terminal, as a sum of: a product of the process agnostic coarse delay value and a predicted delay value of a coarse delay element; a product of the process agnostic fine delay value and a predicted delay value of a fine delay element; a product of the process gnostic coarse delay value and a measured delay value of a coarse delay element; and a product of the process gnostic fine delay value and a measured delay value of a fine delay element.

10. A method, comprising:

routing signals passing to or from input/output (I/O) terminals of an integrated circuit (IC) through an I/O timing module of the IC;

adding propagation delay to the signals in the I/O timing module; and

selecting, by the I/O timing module, delay elements of the I/O timing module to apply to each signal and provide the propagation delay based on an identity of the signal and delay information stored in the I/O timing module for the signal.

11. The method of claim 10, further comprising:

retrieving the delay information from a memory of the I/O timing module; and

determining which of the delay elements to enable in combination to produce the propagation delay.

12. The method of claim 10, wherein the selecting includes determining a number of fine delay elements and a number of coarse delay elements to combine to produce the propagation delay; wherein the fine delay elements provide smaller delay than the coarse delay elements.

13. The method of claim 10, further comprising measuring, prior to the selecting, a first average delay value for each of the coarse delay elements, and a second average delay value for each of the fine delay elements.

14. The method of claim 10, further comprising:

changing, in the I/O delay module, after initialization of propagation delay associated with

one of the I/O terminals, identity of the signal routed to one of the I/O terminals; and

changing, by the I/O delay module, the propagation delay associated with the I/O terminal responsive to the changing of the identity of the signal, and based on the changed identity of the signal.

15. The method of claim 10, further comprising:

presenting, by circuitry external to the I/O timing module, to the I/O delay module: a delay information value; and an I/O terminal identifier; and

setting, by the I/O delay module, the propagation delay associated with the identified I/O terminal by writing the delay information value to a control register associated with the identified I/O terminal.

16. The method of claim 10, wherein the delay information includes a process gnostic coarse delay value, a process gnostic fine delay value, a process agnostic coarse delay value, and a process agnostic fine delay value.

17. The method of claim 16, further comprising computing, by the I/O timing module, the propagation delay as a sum of: a product of the process agnostic coarse delay value and a predicted delay value of a coarse delay element; a product of the process agnostic fine delay value and a predicted delay value of a fine delay element; a product of the process gnostic coarse delay value and a measured delay value of a coarse delay element; and a product of the process gnostic fine delay value and a measured delay value of a fine delay element.

18. An integrated circuit (IC), comprising:

input/output (I/O) terminals configured to pass signals into or out of the IC; and

an I/O timing module configured to add propagation delay to the signals, and including: a plurality of arrays of delay elements, one of the arrays corresponding to each of the I/O terminals; propagation delay value storage that stores a propagation delay value for each of the signals; a calibration controller configured to measure the propagation delay provided by each of the delay elements; and a delay controller configured to select, for each of the signals, based on the measured propagation delay of the delay elements, which of the delay elements to apply to provide the propagation delay specified by the propagation delay value.

19. The IC of claim 18, wherein each of the arrays of delay elements includes: a plurality of coarse delay elements; and a plurality of fine delay elements;

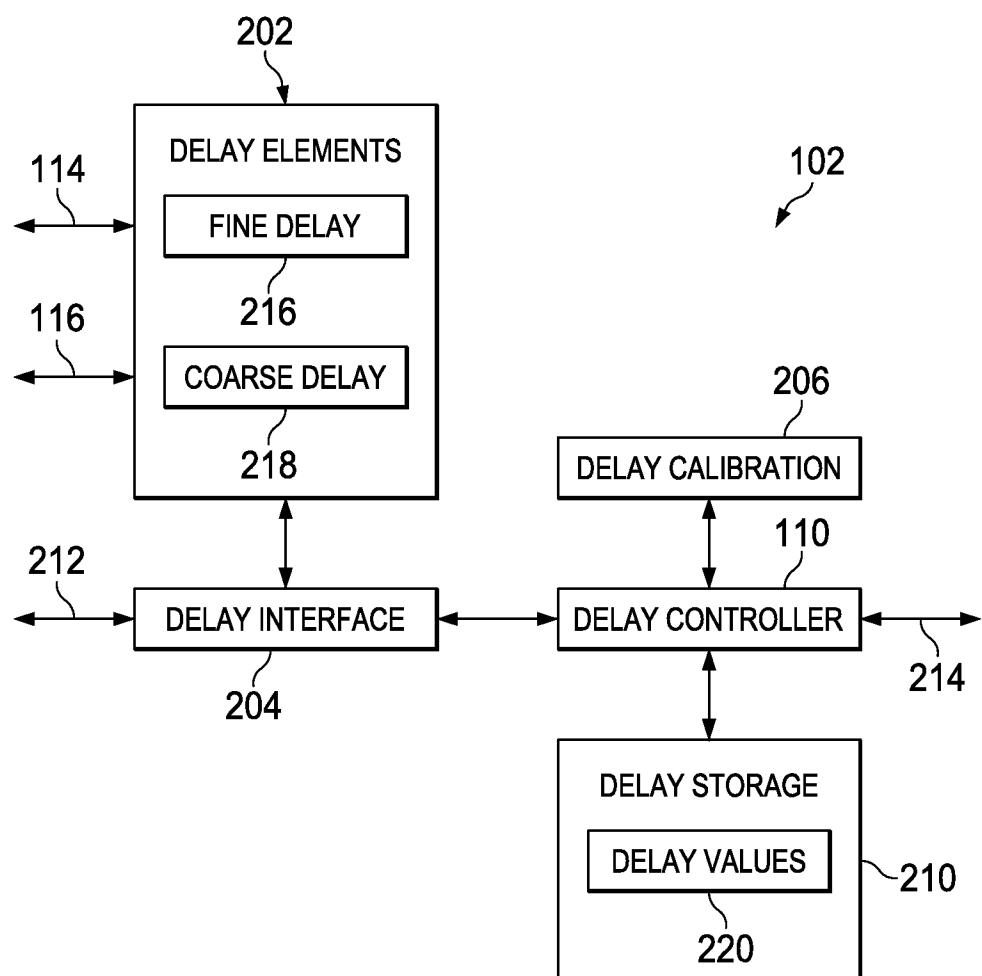
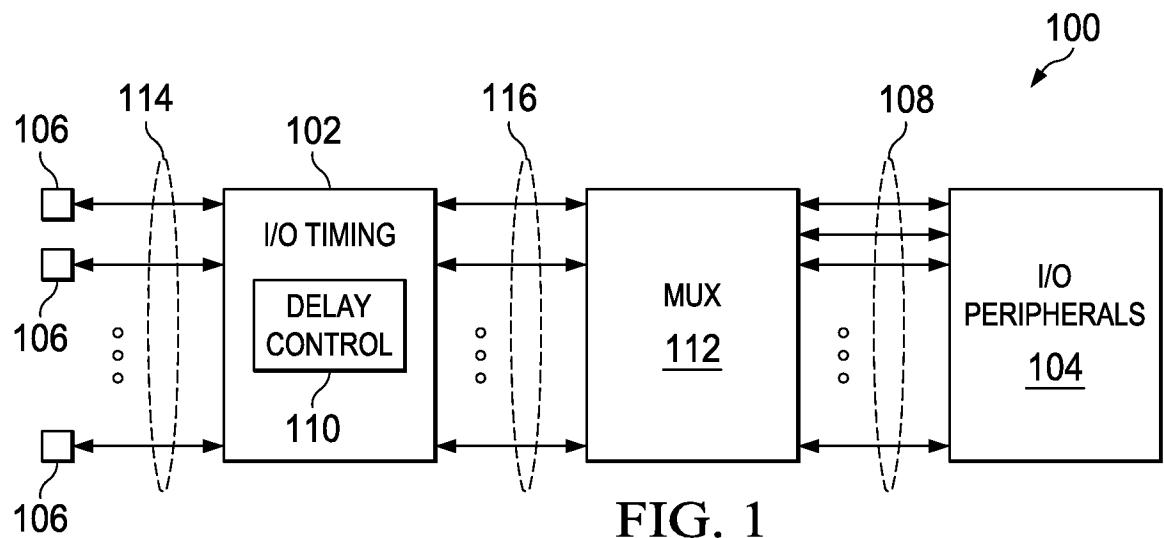
wherein the fine delay elements are configured to provide smaller delay than the coarse

delay elements; and wherein the calibration controller is configured to measure the propagation delay provided by the coarse delay elements and the propagation delay provided by the fine delay elements.

20. The IC of claim 19, wherein each of the propagation delay values includes a process gnostic coarse delay value, a process gnostic fine delay value, a process agnostic coarse delay value, and a process agnostic fine delay value; and the delay controller is configured to compute the propagation delay, for a signal as a sum of: a product of the process agnostic coarse delay value and a predicted delay value of a coarse delay element; a product of the process agnostic fine delay value and a predicted delay value of a fine delay element; a product of the process gnostic coarse delay value and the measured delay of a coarse delay element; and a product of the process gnostic fine delay value and the measured delay of a fine delay element.

21. The IC of claim 20, further comprising an I/O multiplexer configured to selectively route one of a plurality of signals to each I/O terminal; and wherein the delay controller is configured to change the propagation delay associated with the I/O terminal responsive to the I/O multiplexer changing which of the signals is routed to the I/O terminal, and based on an identity of the signal to be routed to the I/O terminal.

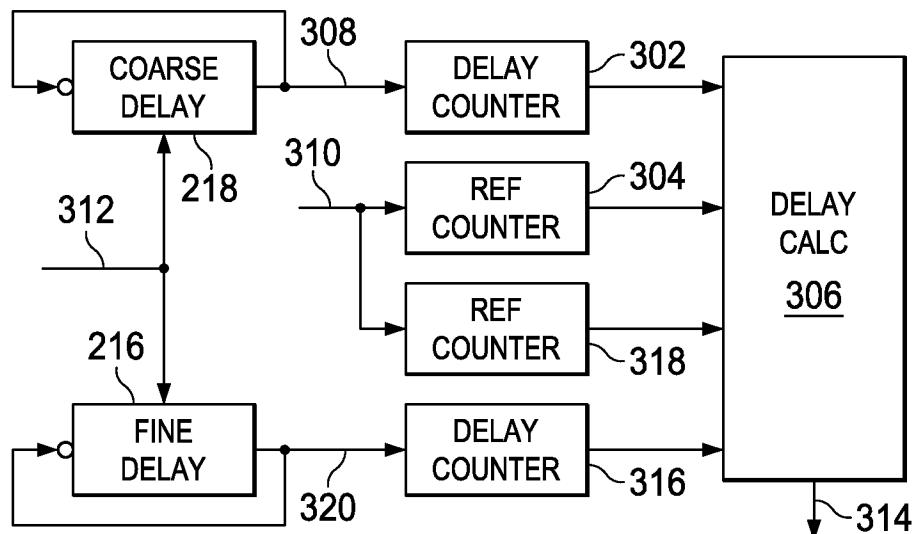
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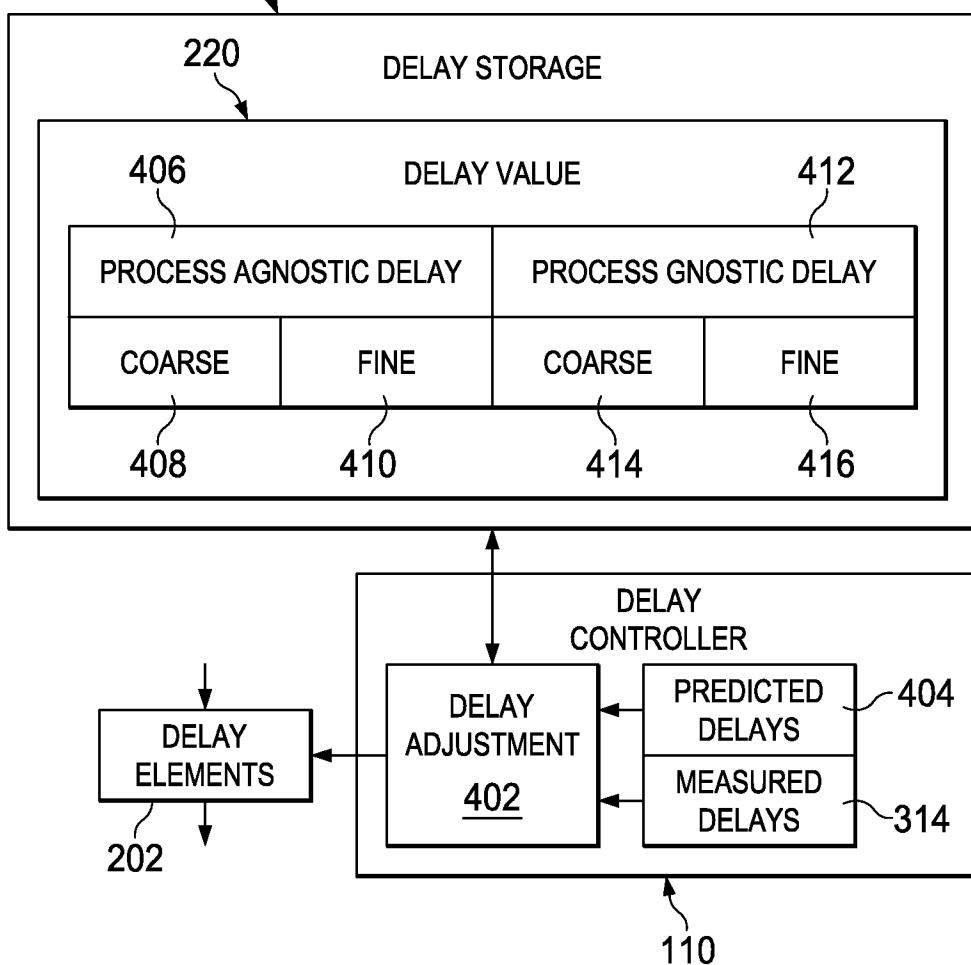
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FIG. 3



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FIG. 4



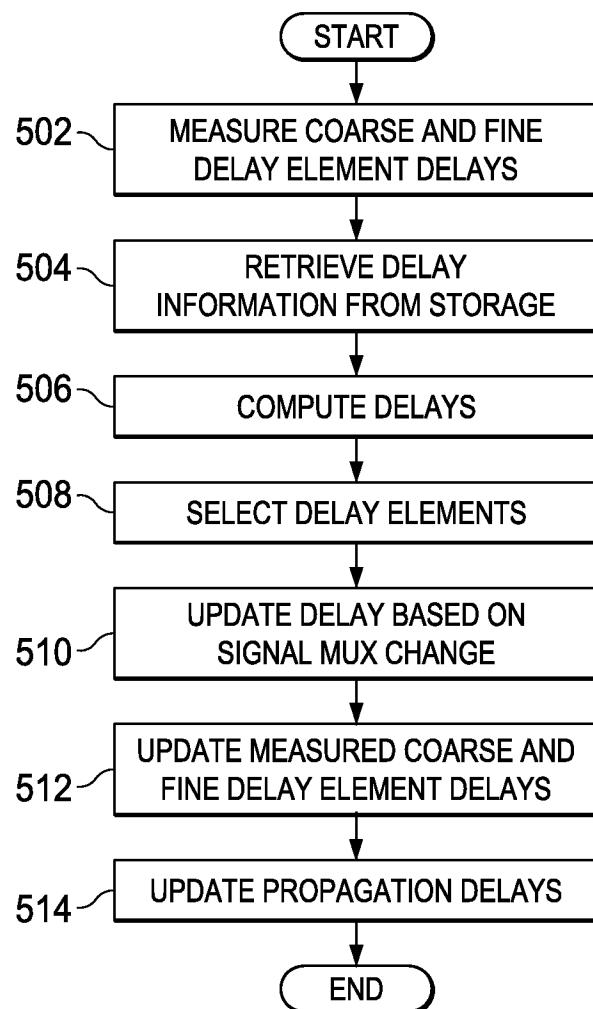


FIG. 5

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 2014/057974

A. CLASSIFICATION OF SUBJECT MATTER

G06F 13/42 (2006.01)

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)

G06F 13/00-13/42, 1/00-1/12, 9/00-9/315, 15/00; GO1M 19/00

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

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

PatSearch (RUPTO internal), USPTO, PAJ, K-PION, Esp@cenet, Information Retrieval System of FIPS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2003/0106361 A1 (HENRY STEVEN GREIDANUS et. al.) 12.01.2003, abstract, paragraphs [0002], [0007], [0021], [0024], [0043]-[0049], [0052], [0055], [0058]-[0060], [0064], [0073], fig. 1, 4	1-2, 6-7, 10-11, 14-15, 18
Y		3-5, 8-9, 12-13, 16-17, 19-21
Y	US 2012/0249200 A1 (WING K. YU) 04.10.2012, abstract, paragraphs [0032]-[0038], fig. 1, 2	3-5, 8-9, 12-13, 16-17, 19-21
A	US 6421784 B1 (INTERNATIONAL BUSINESS MACHINES CORPORATION) 16.07.2002	1-21

 Further documents are listed in the continuation of Box C. See patent family annex.

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Date of the actual completion of the international search

20 March 2015 (20.03.2015)

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