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Hybrid clocking scheme for SERDES physical layer circuits

Abstract

A method for generating clock signals includes dividing an input clock signal to obtain a first in-phase output clock signal, dividing an inverted version of the input clock signal to obtain a first quadrature output clock signal, delaying edges in the input clock signal to obtain a second quadrature output clock signal, selecting a full-rate output to provide a multiphase output clock in a first mode of operation, and selecting a half-rate output to provide the multiphase output clock in a second mode of operation. The first quadrature output clock signal is a quadrature version of the first in-phase output clock signal. The first in-phase output clock signal and the first quadrature output clock signal are included in the full-rate output. The second quadrature output clock signal is included in the half-rate output and is a quadrature version of the input clock signal.

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Background/Summary

TECHNICAL FIELD

(1) The present disclosure generally relates to a clock and data recovery circuits and, more particularly, to circuitry for generating multiple clock signals at different phases.

BACKGROUND

(2) Electronic device technologies have seen explosive growth over the past several years. For example, growth of cellular and wireless communication technologies has been fueled by better communications, hardware, larger networks, and more reliable protocols. Wireless service providers are now able to offer their customers an ever-expanding array of features and services, and provide users with unprecedented levels of access to information, resources, and communications. To keep pace with these service enhancements, mobile electronic devices (e.g., cellular phones, tablets, laptops, etc.) have become more powerful and complex than ever. Wireless devices may include a high-speed bus interface for communication of signals between hardware components.

(3) High-speed serial buses offer advantages over parallel communication links when, for example, there is demand for reduced power consumption and smaller footprints in integrated circuit (IC) devices. In a serial interface, data is converted from parallel words to a serial stream of bits using a serializer and is converted back to parallel words at the receiver using a deserializer. For example, the high-speed bus interface may be implemented using a Peripheral Component Interconnect Express (PCIe) bus, Universal Serial Bus (USB) or Serial Advanced Technology Attachment (SATA), among others.

(4) IC devices may include a serializer/deserializer (SERDES) to transmit and receive through a communication link. In high-speed applications, timing of the operation of a SERDES may be controlled by multiple clock signals. The use of multiple increased frequency clock signals results in increased power consumption. Furthermore, the SERDES generally operates using clock signals that have the same frequency but different phases. Performance, accuracy or reliability of the SERDES may depend on frequency and the phase relationships of the clock signals and drift or other variations in the phase relationships of clock signals can result in errors in received data. Therefore, there is an ongoing need for new techniques that provide reliable lower-power clock generation and calibration circuits for components used to receive clock signals over high-speed serial links.

SUMMARY

(5) Certain aspects of the disclosure relate to IC devices that include a bus interface. The bus interface may include a hybrid clock generation circuit that can be configured to produce multi-phase clock signals for controlling transmissions over a communication bus or sampling and/or capturing data from signals transmitted over the communication bus.

(6) In various aspects of the disclosure, the hybrid clock generation circuit has a divider circuit that includes a first divider coupled to an input clock signal and configured to provide a first in-phase output clock signal in a full-rate output, the first in-phase output clock signal having a frequency

that is half the frequency of the input clock signal, and a second divider coupled to an inverted version of the input clock signal and configured to provide a first quadrature output clock signal in the full-rate output, the first quadrature output clock signal being a quadrature version of the first in-phase output clock signal. The hybrid clock generation circuit also has a delay cell configured to delay edges in the input clock signal and to provide a half-rate output that includes a second quadrature output clock signal that is a quadrature version of the input clock signal. The hybrid clock generation circuit also has a multiplexer configured to select the full-rate output to provide a multiphase output clock when the hybrid clock generation circuit is configured for a first mode of operation, and to select the half-rate output to provide the multiphase output clock when the hybrid clock generation circuit is configured for a second mode of operation. The multiphase output clock may correspond to the multi-phase clock signals used for controlling transmissions over the communication bus or sampling and/or capturing data from the signals transmitted over the communication bus.

(7) In various aspects of the disclosure, a method for generating clock signals includes dividing an input clock signal to obtain a first in-phase output clock signal, dividing an inverted version of the input clock signal to obtain a first quadrature output clock signal, delaying edges in the input clock signal to obtain a second quadrature output clock signal, selecting a full-rate output to provide a multiphase output clock in a first mode of operation, and selecting a half-rate output to provide the multiphase output clock in a second mode of operation. The first quadrature output clock signal is a quadrature version of the first in-phase output clock signal. The first in-phase output clock signal and the first quadrature output clock signal are included in the full-rate output. The second quadrature output clock signal is a quadrature version of the input clock signal. The second quadrature output clock signal is included in the half-rate output. In some implementations, the method may be at least partially performed using the hybrid clock generation circuit.

(8) In various aspects of the disclosure, an apparatus provides means for dividing an input clock signal, including a first divider that is configured to provide a first in-phase output clock signal in a full-rate output, and a second divider that is configured to provide a first quadrature output clock signal in the full-rate output. The first in-phase output clock signal has a frequency that is half the frequency of the input clock signal. The first quadrature output clock signal is a quadrature version of the first in-phase output clock signal. The apparatus further provides means for delaying edges in the input clock signal, including a delay cell that is configured to provide a second quadrature output clock signal in a half-rate output. The second quadrature output clock signal is a quadrature version of the input clock signal. The apparatus further provides means for selecting a multiphase output clock, including a multiplexer that is configured to select the full-rate output to provide the multiphase output clock in a first mode of operation, and select the half-rate output to provide the multiphase output clock in a second mode of operation. In some implementations, the apparatus is configured to operate as a hybrid clock generation circuit.

(9) In certain aspects, the first divider is further configured to provide an inverted version of the first in-phase output clock signal in the full-rate output. The second divider may be further configured to provide an inverted version of the first quadrature output clock signal in the full-rate output.

(10) In certain aspects, the delay cell is configured to provide a second in-phase output clock signal in the half-rate output. The second in-phase output clock signal may be an in-phase version of the input clock signal. The delay cell may be configured to provide an inverted version of the second in-phase output clock signal in the half-rate output. The delay cell may include a compensation section. In the compensation section, a first tracking circuit may be configured to provide cross-skew compensation to rising edges in the second in-phase output clock signal, and a second tracking circuit may be configured to provide cross-skew compensation to falling edges in the second in-phase output clock signal.

(11) In certain aspects, the delay cell is configured to provide an inverted version of the second

quadrature output clock signal in the half-rate output. The delay cell may be configured to receive the input clock signal through a first duty cycle correction circuit. The first duty cycle correction circuit may be configured to decouple the delay cell from the input clock signal when the hybrid clock generation circuit is configured for the first mode of operation. The delay cell may have a second duty cycle correction circuit configured to correct duty cycle distortions caused by the delay cell.

(12) In certain aspects, the first divider and the second divider may be configured to receive the input clock signal through a third duty cycle correction circuit. The third duty cycle correction circuit may be configured to decouple the first divider and the second divider from the input clock signal when the hybrid clock generation circuit is configured for the second mode of operation.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

- (1) FIG. 1 illustrates an example of a system-on-a-chip (SoC) in accordance with certain aspects of the present disclosure.
- (2) FIG. 2 illustrates an apparatus employing interconnected chiplets.
- (3) FIG. 3 illustrates an example of an apparatus in which chiplets are stacked vertically on a substrate.
- (4) FIG. 4 illustrates an example of a system that employs a multi-channel data communication link.
- (5) FIG. 5 illustrates clock distribution in a multi-lane communication interface.
- (6) FIG. 6 illustrates a hybrid clock generation circuit configured in accordance with certain aspects of this disclosure.
- (7) FIG. 7 illustrates an example of a delay cell provided in accordance with certain aspects of this disclosure.
- (8) FIGS. 8-11 illustrate certain aspects of the response to edges in the input clock signal by a delay cell provided in accordance with certain aspects of this disclosure.
- (9) FIG. 12 illustrates examples of clock signaling configured or adapted in accordance with certain aspects of this disclosure.
- (10) FIG. 13 illustrates an example of a divider circuit provided in accordance with certain aspects of this disclosure.
- (11) FIG. 14 is a flowchart of a method for generating clock signals in accordance with certain aspects of this disclosure.

DETAILED DESCRIPTION

(12) The detailed description set forth below in connection with the appended drawings is intended as a description of various configurations and is not intended to represent the only configurations in which the concepts described herein may be practiced. The detailed description includes specific details for the purpose of providing a thorough understanding of various concepts. However, it will be apparent to those skilled in the art that these concepts may be practiced without these specific details. In some instances, well-known structures and components are shown in block diagram form in order to avoid obscuring such concepts.

(13) Several aspects of the invention will now be presented with reference to various apparatus and methods. These apparatus and methods will be described in the following detailed description and illustrated in the accompanying drawings by various blocks, modules, components, circuits, steps, processes, algorithms, etc. (collectively referred to as “elements”). These elements may be implemented using electronic hardware, computer software, or any combination thereof. Whether such elements are implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system.

(14) Data communication links employed by SoCs and other IC devices to connect processors with modems and other peripherals may be operated in accordance with industry or proprietary standards or protocols associated with certain functions or types of devices. According to certain aspects of the disclosure, a serial data link may be used to interconnect electronic devices that are subcomponents of an apparatus such as a cellular phone, a smart phone, a session initiation protocol (SIP) phone, a laptop, a notebook, a netbook, a smartbook, a personal digital assistant (PDA), a satellite radio, a global positioning system (GPS) device, a smart home device, intelligent lighting, a multimedia device, a video device, a digital audio player (e.g., MP3 player), a camera, a game console, an entertainment device, a vehicle component, a wearable computing device (e.g., a smart watch, a health or fitness tracker, eyewear, etc.), an appliance, a sensor, a security device, a vending machine, a smart meter, a drone, a multicopter, or any other similar functioning device.

(15) Certain aspects of the disclosure are applicable to input/output (I/O) circuits that provide an interface between core circuits and memory devices. Many mobile devices employ Synchronous Dynamic Random Access Memory (SDRAM), including Low-Power Double Data Rate SDRAM, which may be referred to as low-power DDR SDRAM, LPDDR SDRAM or, in some instances, LPDDR_x where x describes the technology generation of the LPDDR SDRAM. Later generations of LPDDR SDRAM designed to operate at higher operating frequencies may employ lower voltage levels in the core of an SoC or memory device to mitigate for increased power associated with the higher operating frequencies.

(16) Process technology employed to manufacture semiconductor devices, including IC devices is continually improving. Process technology includes the manufacturing methods used to make IC devices and defines transistor size, operating voltages and switching speeds. Features that are constituent elements of circuits in an IC device may be referred as technology nodes and/or process nodes. The terms technology node, process node, process technology may be used to characterize a specific semiconductor manufacturing process and corresponding design rules. Faster and more power-efficient technology nodes are being continuously developed through the use of smaller feature size to produce smaller transistors that enable the manufacture of higher-density ICs.

(17) Certain examples of circuits, including direct-feedback circuits, are illustrated herein as being implemented using P-type metal-oxide-semiconductor (PMOS) transistors, N-type metal-oxide-semiconductor (NMOS) transistors or some combination of NMOS and PMOS transistors. These circuits are provided by way of example only, and it is contemplated that the concepts disclosed herein can be implemented in circuits that use various other combinations of NMOS and PMOS transistors.

(18) FIG. 1 illustrates an example of an apparatus **100** in which certain components and interconnections are implemented in an SoC. The SoC may include or be coupled to a memory interface/bus **126** that can be adapted according to certain aspects of the present disclosure. The apparatus **100** may include a number of heterogeneous processors, such as a central processing unit (CPU) **102**, a modem processor **104**, a graphics processor **106**, and an application processor **108**. Each processor **102**, **104**, **106**, **108**, may include one or more cores, and each processor/core may perform operations independent of the other processors/cores. The processors **102**, **104**, **106**, **108** may be organized in close proximity to one another (e.g., on a single substrate, die, integrated chip, etc.) so that the processors may operate at a much higher frequency/clock rate than would be possible if the signals were to travel off-chip. The proximity of the cores may also allow for the sharing of on-chip memory and resources (e.g., voltage rails), as well as for more coordinated cooperation between cores.

(19) The apparatus **100** may include system components and resources **110** for managing sensor data, analog-to-digital conversions, and/or wireless data transmissions, and for performing other specialized operations (e.g., decoding high-definition video, video processing, etc.). System components and resources **110** may also include components such as voltage regulators, oscillators, phase-locked loops (PLLs), peripheral bridges, data controllers, system controllers, access ports,

timers, and/or other similar components used to support the processors and software clients running on the computing device. The system components and resources **110** may also include circuitry for interfacing with peripheral devices, such as cameras, electronic displays, wireless communication devices, external memory chips, etc.

(20) The apparatus **100** may further include a Universal Serial Bus controller (the USB controller **112**) or other serial bus controller, one or more memory controllers **114**, and a centralized resource manager (CRM) **116**. The apparatus **100** may also include an input/output module (not illustrated) for communicating with resources external to the SoC, each of which may be shared by two or more of the internal SoC components.

(21) The processors **102**, **104**, **106**, **108** may be interconnected to the USB controller **112**, the memory controller **114**, system components and resources **110**, CRM **116**, and/or other system components via an interconnection/bus module **122**, which may include an array of reconfigurable logic gates and/or implement a bus architecture. Communications may also be provided by advanced interconnects, such as high-performance networks on chip (NoCs).

(22) The interconnection/bus module **122** may include or provide a bus mastering system configured to grant SoC components (e.g., processors, peripherals, etc.) exclusive control of the bus (e.g., to transfer data in burst mode, block transfer mode, etc.) for a set duration, number of operations, number of bytes, etc. In some cases, the interconnection/bus module **122** may implement an arbitration scheme to prevent multiple master components from attempting to drive the bus simultaneously. The memory controller **114** may be a specialized hardware module configured to manage the flow of data to and from a memory **124** via the memory interface/bus **126**.

(23) The memory controller **114** may comprise one or more processors configured to perform read and write operations with the memory **124**. Examples of processors include microprocessors, microcontrollers, digital signal processors (DSPs), field programmable gate arrays (FPGAs), programmable logic devices (PLDs), state machines, gated logic, discrete hardware circuits, and other suitable hardware configured to perform the various functionality described throughout this disclosure. In certain aspects, the memory **124** may be part of the apparatus **100**.

(24) FIG. 2 illustrates an example of an apparatus **200** in which certain components are implemented using multiple chiplets that are interconnected using one or more data communication buses. In one example, the apparatus **200** may be enclosed within a wearable device a portable or wearable processing and/or communication device (each of which being referred to herein as a portable communication device or PCD), sensors, instruments, appliances and other such devices include one or more ICs. These devices may include mobile phones, tablet computers, palmtop computers, portable digital assistants (PDAs), portable game consoles, and other portable electronic devices such as the illustrated smartwatch **210**. PCDs commonly contain integrated circuits or SoCs that include numerous components or subsystems designed to work together to deliver functionality to a user. The various SoC subsystems may communicate with each other via one or more intra-chip data buses or similar data communication interconnects. PCDs may have multiple SoCs that communicate with each other via similar inter-chip interconnects. The ICs are typically packaged in an IC package, which may be referred to as a “semiconductor package” or “chip package.” The IC package typically includes a package substrate and one or more IC chips or other electronic modules mounted to the package substrate to provide electrical connectivity to the IC chips. For example, an IC chip in an IC package may be configured as an SoC. The IC chips are electrically coupled to other IC chips and/or to other components in the IC package through electrical coupling to metal lines in the package substrate. The IC chips can also be electrically coupled to other circuits outside the IC package through electrical connections of external metal interconnects (e.g., solder bumps) of the IC package.

(25) Chiplet technology can be used to address some of the performance, power and size design requirements for complex SoCs used in certain mobile or wearable devices. The block diagram in

FIG. 2 illustrates certain aspects of an apparatus **200** that can be constructed using chiplets. The apparatus **200** may be configured by selecting a combination of chiplets that implement certain subsystems or distinct functional elements. In the illustrated example, the apparatus **200** includes a set of primary chiplets **202** that enable the apparatus **200** to perform core processing, security and communication functions. The set of primary chiplets **202** include a processor, memory and one or more modems. The illustrated apparatus **200** also includes a set of application-specific chiplets **204** that includes an application processor, display driver, camera interface and audio controller. In a remote sensing device or appliance, the audio-visual components could be omitted and may be replaced with analog-to-digital controllers, for example.

(26) The apparatus **200** may include a variety of processing engines, such as central processing units (CPUs) with multiple cores, graphical processing units (GPUs), digital signal processors (DSPs), neural processing units (NPU), wireless transceiver units (also referred to as modems), peripherals, display and imaging interfaces, etc. Each of these subsystems and other functional elements can be implemented as an individual chiplet, or as a combination of chiplets. The chiplets included in the apparatus **200** can be proprietary or may be acquired from a variety of sources. An SoC may be constructed from chiplets manufactured at different process nodes and/or operated at different voltages.

(27) FIG. 3 illustrates an example of an SoC **300** in which certain chiplets **304**, **306**, **308** are stacked vertically on a substrate **310**. Some chiplets can be included in stacks that are deployed across the surface of the substrate **310**, while other chiplets may be individually mounted on the surface of the substrate. Chiplets may be mounted on the surface of the substrate using solder balls **302** that provide electrical and/or thermal coupling between substrate and the mounted chiplets. An interconnect structure may be formed that enables chiplets **304**, **306**, **308** in a stack of chiplets to communicate with one another, with other chiplets mounted on the substrate **310** and with input/output structures that connect the apparatus **200** with other circuits, displays, imaging sensors and other peripherals with an apparatus.

(28) The use of chiplets can reduce the areal size of the substrate **310** and increase three-dimensional packing density. The constituent chiplets may provide complex features and high performance within a smaller form-factor operated at lower power specifications. Moreover, each chiplet may define multiple power domains, operate at different frequencies and different chiplets may manage power/frequency modes independently and. In some instances, two or more chiplets may be operated in mutually exclusive power states. Additionally, operating conditions for an SoC depend on the type, number and arrangement of chiplets included on the substrate in addition to the modes of operation defined by applications. It is necessary to consider power usage by all chiplets in the SoC in order to ensure compliance with power budgets assigned for an application or device. Conventional chiplet-based implementations suffer from limitations that include complex or difficult interconnect routing, local hotspots arising from routing congestion caused by connection architecture and challenges to signal timing specifications. In certain examples, local hotspots can arise from routing congestion, increased feature complexity and circuit concentrations. In certain examples, signal timing specifications can be compromised due to the necessity for an increased number of isolation clamps due to logic placement, number of voltage domains and reduced floorplan. Long wire crossings between chiplets can cause routing congestion.

(29) Each chiplet in an SoC may be included to perform a specific function or type of function and the configuration of the chiplets can introduce further complexities and challenges for designers. For example, one chiplet may include radio frequency front end circuits that produce high frequency signals ranging up to 5 GHz or more, and may further include interfaces that are used by low-frequency power management circuits. A designer may import previously defined circuit blocks to implement some of the internal functions. These circuit blocks may be referred to as macros. Imported circuit blocks for a given process technology may be described, characterized or defined by a set of masks, hardware description language, specifications and test data.

Commercially available or proprietary circuit blocks may be referred to as hard macros. Hard macros are tested and verified for a set of design and operating specifications. It is common for hard macros and other circuit blocks to define multiple power domains.

(30) FIG. 4 illustrates an example of a system that employs a multi-channel data communication link **480** to couple a modem **400** with a wireless transceiver **440**. The data communication link **480** includes data channels **482** and **486** and a clock channel **484** that provide a transmission medium through which signals propagate between devices. In the illustrated example, a modem **400** transmits data in a first signal over a first data channel **482** to a wireless transceiver **440** and receives data in a second signal transmitted over a second data channel **486**. Data signals are transmitted over the data channels **482** and **486** in accordance with timing information provided by a bus clock signal **430** transmitted over the clock channel **484**.

(31) The modem **400** may include a serializer **402** configured to convert n-bit parallel data elements, bytes or words into a serial data stream for transmission in a transmit data signal **422** over the first data channel **482**. The transmit data signal **422** may be preconditioned by a pre-equalizing circuit, such as the illustrated digital feed-forward equalizer (the FFE **404**), in order to combat or compensate for signal distortions attributable to inter-symbol interference (ISI), reflection and other effects that can be expected to limit bandwidth in first data channel **482**. The preconditioned transmit data signal **424** output by the FFE **404** is provided to a driver circuit **406** that is configured to drive the first data channel **482**.

(32) The modem **400** may include a serializer **402** configured to convert n-bit parallel data elements, bytes or words into a serial data stream for transmission in a serialized data signal **422**. The serialized data signal **422** may be preconditioned by a pre-equalizing circuit, such as the illustrated digital feed-forward equalizer (the FFE **404**), in order to combat or compensate for signal distortions attributable to inter-symbol interference (ISI), reflection and other effects that can be expected to limit bandwidth in the first data channel **482**. A preconditioned data signal **424** output by the FFE **404** is provided to a driver circuit **406** that is generate configured to generate and transmit a differential transmit data signal **426** over the first data channel **482**.

(33) The wireless transceiver **440** can be configured to process a data signal **460** received over the first data channel **482**. The data signal **460** may be provided to a differential receiver **442**, which may include or cooperate with an equalizing circuit. In one example, continuous time linear equalization (CTLE) may be used to compensate for certain losses experienced in the first data channel **482**. The first data channel **482** may be characterized in some respects as a low-pass filter. In the illustrated example, the differential receiver **442** outputs an equalized data signal **462** that is sampled by a slicer **444**. The slicer **444** may be implemented using a D-flipflop or the like and may be configured to capture signaling state of the equalized data signal **462** under the control of edges in a sampling clock signal **472** generated by a clock and data recovery (CDR) circuit **448**. The output of the slicer **444** may be provided to a deserializer **446** that is clocked in accordance with one or more clock signals provided by the CDR circuit **448**. The CDR circuit **448** may be configured to delay or phase shift a receiver clock signal **470** to ensure that edges in the sampling clock signal **472** are timed to optimize sampling reliability.

(34) In the illustrated wireless transceiver **440**, the receiver clock signal **470** is derived from a received bus clock signal **474** from the clock channel **484**. A differential receiver **452** coupled to the clock channel **484** may be configured to equalize the received bus clock signal **474**, and a duty cycle correction circuit **450** may be used to adjust the duty cycle of the receiver clock signal **470**. The receiver clock signal **470** is provided to a serializer **454** that is configured to convert n-bit parallel data elements, bytes or words into a serial data stream for transmission in a serialized data signal **464**. The serialized data signal **464** may be preconditioned by a pre-equalizing circuit, such as the illustrated FFE **456**, in order to combat or compensate for signal distortions attributable to ISI, reflection and other effects that can be expected to limit bandwidth in the second data channel **486**. A preconditioned data signal **466** output by the FFE **456** is provided to a driver circuit **458** that

is configured generate and transmit a differential transmit data signal **468** over the second data channel **486**.

(35) The illustrated modem **400** can be configured to process a data signal **432** received over the second data channel **486**. The data signal **432** may be provided to a differential receiver **420**, which may include or cooperate with an equalizing circuit. In one example, CTLE may be used to compensate for certain losses experienced in the second data channel **486**. The second data channel **486** may be characterized in some respects as a low-pass filter. In the illustrated example, the differential receiver **420** outputs an equalized data signal **428** that is sampled by a slicer **418**. The slicer **418** may be implemented using a D-flipflop or the like and may be configured to capture signaling state of the equalized data signal **428** under the control of edges in a sampling clock signal **434** generated by a CDR circuit **414**. The output of the slicer **418** may be provided to a deserializer **416** that is clocked in accordance with one or more clock signals provided by the CDR circuit **414**. The CDR circuit **414** may be configured to delay or phase shift a transmitter clock signal to ensure that edges in the sampling clock signal **434** are timed to optimize sampling reliability.

(36) A clock generation circuit, including the illustrated phase locked loop **408**, may generate multiple clock signals **436a**, **436b**, **436c** used by the modem **400**. One or more of the clock signals **436a**, **436b**, **436c** may be a divided version of a base clock signal generated by the PLL **408**. One or more of the clock signals **436a**, **436b**, **436c** may be phase shifted with respect to the base clock signal. In one example, the serializer **402** may produce the serialized data signal **422** using timing provided by a first clock signal **436a**. In another example, the bus clock signal **430** transmitted over the clock channel **484** may be derived from a second clock signal **436b**. In some instances, a duty cycle correction circuit **410** may be used to adjust the duty cycle of the second clock signal **436b** and to provide an input to a driver circuit **412** that is configured drive the clock channel **484**. In another example, the CDR circuit **448** may generate the sampling clock signal **434** from a third clock signal **436c**.

(37) Limiting power consumption presents a major challenge in SERDES-based design. In mobile communication devices, reducing power consumption can increase battery life between charges. The switching frequency of physical layer (PHY) circuits in communication interfaces can be a major factor in power consumption of an apparatus. Accordingly, power consumption is a parameter that must be considered when the PHY circuits are designed to meet ever-increasing demands for data rates and corresponding signaling rates associated with the communication interface. Demands for higher data rates and increased performance from SERDES-based PHY circuits are a consequence of continual advances in process technology and changing industry and proprietary standards. Moreover, PHY circuits are typically required to maintain backward compatibility to all previous generations of technology while supporting the higher data rates required by ever-evolving standards, necessitating increased numbers of transistors. Clock generation circuits for SERDES-based PHY circuits are frequently determinative of maximum data rates for an application and power consumption increases with frequency. Increasing the complexity of clock generation circuits can further increase power consumption of the PHY circuits.

(38) In conventional SERDES-based PHY circuits, clock and data recovery (CDR) circuits typically include a phase interpolator (PI) that requires precise quadrature clock generation to produce the 4 phases of a clock signal used by the PI. In some examples, a phase interpolator selects a phase for an output signal by mixing two phase versions of an input signal. The phase of the output signal is selected by weighting the contributions of the two phase versions of an input signal in the output signal. For example, the phase versions of the input signal may be quadrature (I and Q) signals that are separated by a 90° phase shift and the output signal may be generated with a phase shift that can be changed in step intervals. The output signal may have substantially the same phase as the Q signal when the I input signal is weighted at 0% and the Q input signal is weighted

at 100%. The phase of the output signal may be modified by stepwise adding and/or removing weight to the inputs. The use of multiple phase-shifted higher frequency clock signals by a SERDES is associated with significant power consumption including power consumption by the phase interpolator.

(39) Certain aspects of this disclosure relate to clock generation circuits that can support a wide range of data rates while maintaining low design complexity and low power consumption. In one example, a clock generation circuit disclosed herein can operate at low power while delivering high quality clock signals to a transceiver (TX/RX) circuit. A clock generation circuit provided in accordance with certain aspects of this disclosure may use clock signals provided by a PLL and can operate at low power over a wide range of data rates and can be adapted to support process scaling. A clock generation circuit provided in accordance with certain aspects of this disclosure can generate robust clock signals with precise phase relationships. A clock generation circuit provided in accordance with certain aspects of this disclosure can be used with a variety of SERDES architectures, and can support multiple data rates required by certain SERDES-based PHY applications.

(40) According to certain aspects of this disclosure, clock generation in a SERDES-based PHY can be partitioned between a high-frequency clock generation path and a lower-frequency clock generation path, of which one clock generation path is active at any time. In some implementations, a fixed frequency source clock signal may be used by both clock generation paths. In some implementations, the frequency of the source clock signal may be varied.

(41) FIG. 5 is a conceptual drawing **500** that illustrates clock distribution in an example of a PHY in a multi-lane communication interface. In the illustrated example, each lane of the communication interface is provided using a connector **5100-510N**, interconnect or wire. A set of transceivers **5080-508N** is coupled to a corresponding connector **5100-510N** and each transceiver **5080-508N** may receive a fixed-frequency clock signal **524** that can be used to generate multiphase clock signals that control transmission of data bits over the corresponding connector **5100-510N** and/or that control sampling or capturing of data in signal received over the corresponding connector **5100-510N**.

(42) In the illustrated example, a clock generation or recovery circuit **502** includes a phase locked loop circuit (the PLL **512**) that can be configured to generate a source clock signal **520** at a predefined or desired frequency. The output clock signal **522** produced by the clock generation or recovery circuit **502** may be derived from the source clock signal **520**, and may have the same frequency as the source clock signal **520**. In some instances, the output clock signal **522** has a different frequency than the source clock signal **520**. For example, the source clock signal **520** may be provided to a divider and/or multiplexer circuit **514** that can be used to select between the source clock signal **520** and a lower frequency version of the source clock signal **520**. The output clock signal **522** may be buffered for distribution and to provide the fixed-frequency clock signal **524** to the transceivers **5080-508N**.

(43) A PLL **512** and associated clock distribution circuits **504** can be simplified and optimized for use at a predefined frequency when the PHY is configured to use a fixed-frequency clock signal **524** in accordance with certain aspects of this disclosure. Each transceiver **5080-508N** includes quadrature clock generation circuits **5160-516N** that can generate multiple phases for higher-frequency clock and lower-frequency clock paths. In certain implementations, circuits in the high-frequency clock path operate in a half-rate mode, while circuits in the lower-frequency clock path operate in a full-rate mode. In one example, the high-frequency clock path support data rates of 24 Gigabits per second (Gbps) or more while the low-frequency clock path support data rates of 12 Gbps or less. In other examples, the high-frequency clock path may support data rates that are less than 24 Gbps and/or the low-frequency clock path can support data rates that are greater than 12 Gbps. The use of half-rate mode in the high-frequency clock path can permit the PLL **512** and clock distribution circuits **504** to be operated at lower frequencies.

(44) FIG. 6 illustrates a hybrid clock generation circuit **600** configured in accordance with certain aspects of this disclosure. In one example, the hybrid clock generation circuit **600** is provided in a transceiver of a multi-lane communication interface. The hybrid clock generation circuit **600** provides a half-rate path **602** that may be used for higher data rate communication and a full-rate path **604** that may be used for lower data rate communication. In one example, the half-rate path **602** may be configured to support data rates of 24 Gigabits per second (Gbps) or more, while the full-rate path supports data rates of 12 Gbps or less. In other examples, the half-rate path **602** may support data rates that are less than 24 Gbps and/or the full-rate path **604** supports data rates that are greater than 12 Gbps. A common input clock signal **610** is distributed to the half-rate path **602** and the full-rate path **604**.

(45) In the illustrated example, the half-rate path **602** and the full-rate path **604** generate multiphase clock signals that can be used to capture data from a communication channel or to control transmission of data bits over the communication channel. The multiphase clock signals include a differential in-phase clock signal and a differential quadrature clock signal that is phase-shifted by 90° with respect to the differential in-phase clock signal. A differential signal includes two complementary signals that are phase-shifted by 180° with respect to one another.

(46) The half-rate path **602** includes a duty cycle correction circuit (DCC **612**) and a delay module **614** configured in accordance with certain aspects of this disclosure. The DCC **612** receives a buffered version of the input clock signal **610** and provides a corrected clock signal **616** to the delay module **614**. In some examples, the input clock signal **610** and/or the corrected clock signal **616** may be differential signals. In the illustrated example, the input clock signal **610** and the corrected clock signal **616** are single-ended signals. The delay module **614** may invert the corrected clock signal **616** or otherwise generate an inverted version of the corrected clock signal **616** that is phase-shifted by 180° with respect to the corrected clock signal **616**. In some implementations, the delay module **614** includes a first delay cell that is configured to produce an output clock signal that is phase-shifted by 90° with respect to the input clock signal **610** and includes a second delay cell that is configured to produce an output clock signal that is 614 is phase-shifted by 90° with respect to an inverted version of the input clock signal **610**.

(47) The term half-rate as used herein refers to the use of a clock signal that is half the frequency of the data signal, and different phases of the half-rate clock signal can be used to capture bits of data from different bit transmission intervals **650**. The timing diagram **640** illustrates an example of a full-rate clock signal **644** and a half-rate clock signal **646** that may be used to capture data from a data signal **642**. The full-rate clock signal **644** has a period that matches the duration of each bit transmission interval **650** (i.e., the duration of transmission of each of Bit n -Bit $n+4$), and a data bit can be captured during each cycle of the full-rate clock signal **644**. In the illustrated example, the data bits are captured using rising edges of the full-rate clock signal **644**, which are timed to occur at the midpoint **648.sub.n-648n+4** of each bit transmission interval **650**. In other examples, the falling edges of the full-rate clock signal **644** may be used to capture data bits. In some implementations, data bits are captured near the end of each bit transmission interval **650**.

(48) The half-rate clock signal **646** has a period that corresponds to twice the duration of each bit transmission interval **650**, and a data bit must be captured during each half-cycle of the half-rate clock signal **646**. That is, data bits are captured using both rising edges and falling edges of the half-rate clock signal **646**, which are timed to occur at the midpoint **648.sub.n-648n+4** of each bit transmission interval **650** in the illustrated example. In other examples, data bits are captured near the end of each bit transmission interval **650**.

(49) The output **618** of the half-rate path **602** includes multiple phase versions of the input clock signal **610**, including a differential in-phase version of the input clock signal (hr_clkI and hr_clkIb) and a differential quadrature version of the input clock signal (hr_clkQ and hr_clkQb), which is phase-shifted by 90° with respect to the differential in-phase version of the input clock signal. Each of the complementary signal pairs (hr_clkI/hr_clkIb and hr_clkQ/hr_clkQb) includes two signals

that are phase-shifted by 180° with respect to one another. Therefore, the output **618** of the half-rate path **602** includes four phase versions of the input clock that are spread at nominal 90° intervals (i.e., 0° phase shifted, 90° phase shifted, 180° phase shifted and 270° phase shifted), and that can be used to capture data bits during each half-cycle of the input clock signal **610**. The half-rate path **602** can significantly reduce power consumption and clock distribution design complexity in high data rate modes of operation.

(50) Each delay cell in the delay module **614** may employ a delay line structure to produce the output **618** of the half-rate path **602**. In one example, each delay cell may be implemented using a delay line structure that has two delay stages. A delay line structure that is limited to 2 delay stages can operate at significantly higher clock frequencies than is possible with delay line structure that use more than 2 delay stages. Minimizing the delay stages in the delay line structure can yield significant power savings, can enable controllable and/or tunable delays to be closely matched, and can reduce susceptibility to the effects of noise in the input clock signal **610**.

(51) The full-rate path **604** includes a duty cycle correction circuit (i.e., the DCC circuit **622**) and a divider circuit **624** that can be implemented using complementary metal-oxide-semiconductor (CMOS) digital circuits. In one example, the divider circuit **624** can be implemented using one or more flipflops, each triggered by an edge in the input clock signal **610**. The DCC circuit **622** receives a buffered version of the input clock signal **610** and provides a corrected clock signal **626** to the divider circuit **624**. In the illustrated example, the input clock signal **610** and the corrected clock signal **616** are single-ended signals. In other examples, the input clock signal **610** and/or the corrected clock signal **616** may be differential signals.

(52) The divider circuit **624** may be implemented using a simple CMOS divide-by-2 divider to generate an output **628** with four phases for use in full-rate modes of operation that provide lower data rates. The divider circuit **624** can be constructed using robust simple circuits that operate with low power and are tolerant of process, voltage or temperature (PVT) variations. For example, a divider circuit **624** based on CMOS circuitry can be easily scaled as process technology advances.

(53) The output **628** of the full-rate path **604** includes multiple phase versions of the input clock signal **610**, including a differential in-phase version of the input clock signal (fr_clkI and fr_clkIb) and a differential quadrature version of the input clock signal (fr_clkQ and fr_clkQb), which is phase-shifted by 90° with respect to the differential in-phase version of the input clock signal. Each of the complementary signal pairs (fr_clkI/fr_clkIb and fr_clkQ/fr_clkQb) includes two signals that are phase-shifted by 180° with respect to one another. Therefore, the output **628** of the full-rate path **604** nominally includes four phase versions of the divided input clock, the versions being spread at nominal 90° intervals that can be used to capture data bits during each cycle of the input clock signal **610**. That is, when the input clock signal **610** has a frequency of $2x$ Hz, the output **628** of the full-rate path **604** includes four signals with a frequency of x Hz, including signals with a 0° phase shift, a 90° phase shift, a 180° phase shift and a 270° phase shift. In one example, the input clock signal **610** has a frequency of 12 GHz and the output **628** of the full-rate path **604** includes four signals with a frequency of 6 GHz.

(54) The hybrid clocking scheme disclosed herein may be employed in communication links that employ short-reach and clock forwarding SERDES architectures. Certain aspects are applicable to inter-chiplet communication, LPDDR SDRAM interfaces, in addition to data communication links used to couple functional elements within an apparatus according to proprietary or standards-defined protocols.

(55) In one aspect of this disclosure, power savings can be accrued by disabling the full-rate path **604** when the output **618** of the half-rate path **602** is used to control capture of data bits, and by disabling the half-rate path **602** when the output **628** of the full-rate path **604** is used to control capture of data bits. The half-rate path **602** may be disabled by blocking or decoupling the input clock signal **610** from one or more circuits of the half-rate path **602**. In one example, a control input **632** provided to the DCC **612** in the half-rate path **602** may be configured to block the input clock

signal **610**. The control input **632** may also provide configuration or feedback settings used to correct duty cycle when the half-rate path **602** is active. The control input **632** may be provided by a processor or controller in the PHY or by a processing circuit that is configured to control communication through the PHY.

(56) The full-rate path **604** may be disabled by blocking or decoupling the input clock signal **610** from one or more circuits of the full-rate path **604**. In one example, a control input **634** provided to the DCC circuit **622** in the full-rate path **604** may be configured to block the input clock signal **610**. The control input **634** may also provide configuration or feedback settings used to correct duty cycle when the full-rate path **604** is active. The control input **634** may be provided by a processor or controller in the PHY or by a processing circuit that is configured to control communication through the PHY.

(57) A multiplexer **606** may be used to select between the output **618** of the half-rate path **602** and the output **628** of the full-rate path **604** to provide the multiphase output **620** of the hybrid clock generation circuit **600**. The multiplexer may select the multiphase output **620** of the hybrid clock generation circuit **600** based on the configuration of a control input **636**. The control input **636** may be provided by a processor or controller in the PHY or by a processing circuit that is configured to control communication through the PHY.

(58) FIG. 7 illustrates an example of a delay cell **700** provided in accordance with certain aspects of this disclosure. In one example, the delay cell **700** may be used in the delay module **614** in the half-rate path **602** illustrated in FIG. 6. The illustrated delay cell **700** includes a main delay generation section **810** (see FIGS. 8 and 9), a compensation section **1010** (see FIGS. 10 and 11) and, in some implementations, a duty cycle correction circuit (the DCC circuit **708**). In some respects, the main delay generation section **810** is configured as a push-pull amplifier that receives an input clock signal **710a** and drives an output clock signal **740**.

(59) A first input circuit **702a** in the main delay generation section **810** includes an input PMOS transistor **712a** coupled in series with two NMOS transistors **714a**, **716a** between the rails of a power supply (VDD and ground in FIGS. 7-11). The input PMOS transistor **712a** has a source coupled to VDD and a gate that is coupled to the input clock signal **710a**. The drain of the input PMOS transistor **712a** provides the output **720a** of the first input circuit **702a**. Furthermore, the drain of input PMOS transistor **712a** is coupled to ground through two series coupled NMOS transistors **714a** and **716a**, of which at least NMOS transistor **716a** is tunable. The gates of the NMOS transistors **714a** and **716a** receive respective bias voltages **742** and **744** that can be configured to control the amplitude of current flowing from the source of NMOS transistor **714a** to ground through NMOS transistor **716a**. In one example, NMOS transistor **716a** may be constructed using multiple NMOS transistors that can be coupled in parallel. A tuning code may control switches that select or activate a quantity of NMOS transistors or individual NMOS transistors to be coupled in parallel. The bias voltage **744** is coupled to the base of at least the selected or activated NMOS transistors. In another example, NMOS transistor **716a** may be tuned using an analog control signal. NMOS transistor **716a** may be used to tune the amplitude of current flowing from the source of NMOS transistor **714a** to ground.

(60) The bias voltages **742** and **744** provided to the gates of NMOS transistors **714a** and **716a**, respectively, may be generated using a bandgap reference current (I_e). The bias voltages **742** and **744** control the level of current that flows through NMOS transistors **714a** and **716a** to ground, and the NMOS transistors **714a** and **716a** may be characterized as a current source or as an I_e current source. The level of current flowing through the NMOS transistors **714a** and **716a** can be controlled, calibrated or tuned to adjust the rate at which edges rise in the output clock signal **740**. The level of current flowing through the NMOS transistors **714a** and **716a** may be used to tune the delay between the input clock signal **710a** and the output clock signal **740**.

(61) The output **720a** of the first input circuit **702a** is coupled to an input of a first output driver circuit **704a**. In the illustrated example, a first PMOS output transistor **726a** has a gate that is

coupled to the drain of the input PMOS transistor **712a**, a source that is coupled to VDD, and a drain that is configured to drive the output clock signal **740**. The output clock signal **740** is also coupled to an output of the compensation section **1010**, as will be discussed below.

(62) A second input circuit **702b** in the main delay generation section **810** includes an input NMOS transistor **712b** coupled in series with two PMOS transistors **714b**, **716b** between the rails of the power supply. The input NMOS transistor **712b** has a source coupled to ground and a gate that is coupled to the input clock signal **710a**. The drain of the input NMOS transistor **712b** provides the output **720a** of the second input circuit **702b**. The drain of input NMOS transistor **712b** is also coupled to VDD through two series-coupled PMOS transistors **714b** and **716b**, of which at least PMOS transistor **716b** is tunable. The gates of the PMOS transistors **714b** and **716b** receive respective bias voltages **746** and **748** that can be configured to control the amplitude of current flowing from the source of PMOS transistors **714b** to ground through PMOS transistor **716b**. In one example, PMOS transistor **716b** may be constructed using multiple PMOS transistors that can be coupled in parallel. A tuning code may control switches that select or activate a quantity of PMOS transistors or individual PMOS transistors to be coupled in parallel. The bias voltage **746** is coupled to the base of at least the selected or activated PMOS transistors. In another example, PMOS transistor **716b** may be tuned using an analog control signal. PMOS transistor **716b** may be used to tune the amplitude of current flowing from the source of PMOS transistor **714b** to ground.

(63) The bias voltages **746** and **748** provided to the gates of PMOS transistors **714b** and **716b**, respectively, may be generated using a bandgap reference current (I_e). The bias voltages **746** and **748** control the level of current that flows through PMOS transistors **714b** and **716b** to ground, and the PMOS transistors **714b** and **716b** may be characterized as a current source or as an I_e current source. The level of current flowing through the PMOS transistors **714b** and **716b** can be controlled, calibrated or tuned to adjust the rate at which edges fall in the output clock signal **740**. The level of current flowing through the PMOS transistors **714b** and **716b** may be used to tune the delay between the input clock signal **710a** and the output clock signal **740**.

(64) The output **720b** of the second input circuit **702b** is coupled to an input of a second output driver circuit **704b**. In the illustrated example, a first NMOS output transistor **726b** has a gate that is coupled to the drain of the input NMOS transistor **712b**, a source that is coupled to ground, and a drain that is configured to drive the output clock signal **740**. The output clock signal **740** is driven by the first input circuit **702a** and second input circuit **702b** in a push-pull manner with contributions from the compensation section **1010**.

(65) The compensation section **1010** includes a first tracking circuit **706a** and a second tracking circuit **706b** which receive a complementary version of input clock signal **710a**, which is referred to herein as the complementary input clock signal **710b**. The tracking circuits **706a**, **706b** may be configured to compensate for PVT variations. Each of the tracking circuits **706a**, **706b** includes a current source that is substantially similar to a current source provided in a corresponding input circuit **702a**, **702b**. The first tracking circuit **706a** can be configured such that its current source tracks the corresponding current source in the second input circuit **702b**. In the illustrated example, the current source in the first tracking circuit **706a** includes PMOS transistors **734a**, **736a** that are arranged, configured and controlled in a substantially similar manner to the PMOS transistors **714b**, **716b** that provide the current source in the second input circuit **702b**. The second tracking circuit **706b** can be configured such that its current source tracks the corresponding current source in the first input circuit **702a**. In the illustrated example, the current source in the second tracking circuit **706b** includes NMOS transistors **734b**, **736b** that are arranged, configured and controlled in a substantially similar manner to the NMOS transistors **714a**, **716a** that provide the current source in the first input circuit **702a**.

(66) The first tracking circuit **706a** may be further configured to respond to edges in the complementary input clock signal **710b** in order to provide cross-skew compensation to rising edges in the output clock signal **740**. The second tracking circuit **706b** may be further configured to

respond to edges in the complementary input clock signal **710b** in order to provide cross-skew compensation to falling edges in the output clock signal **740**.

(67) The first tracking circuit **706a** includes an input NMOS transistor **732a** coupled in series with two PMOS transistors **734a**, **736a** between the rails of a power supply (VDD and ground in FIG. 7). The input NMOS transistor **732a** has a source coupled to ground and a gate that is coupled to the complementary input clock signal **710b**. The drain of the input NMOS transistor **732a** provides the output **730a** of the first tracking circuit **706a**. The drain of input NMOS transistor **732a** is coupled to VDD through two series coupled PMOS transistors **734a** and **736a**, of which at least PMOS transistor **736a** is tunable. The gates of the PMOS transistors **734a** and **736a** receive respective bias voltages **746** and **748** that can be configured to control the amplitude of current flowing from VDD to the source of PMOS transistor **734a** through PMOS transistor **736a**. In one example, PMOS transistor **736a** may be constructed using multiple PMOS transistors that can be coupled in parallel. A tuning code may control switches that select or activate a quantity of PMOS transistors or individual PMOS transistors to be coupled in parallel. The bias voltage **746** is coupled to the base of at least the selected or activated PMOS transistors. In another example, PMOS transistor **736a** may be tuned using an analog control signal. PMOS transistor **736a** may be used to tune the amplitude of current flowing from the source of PMOS transistor **734a** to ground.

(68) The bias voltages **746** and **748** provided to the gates of PMOS transistors **734a** and **736a**, respectively, may be generated using a bandgap reference current (I_e). The bias voltages **746** and **748** control the level of current that flows through PMOS transistors **734a** and **736a** to ground, and the PMOS transistors **734a** and **736a** may be characterized as a current source or an I_e current source. The level of current flowing through the PMOS transistors **734a** and **736a** can be controlled, calibrated or tuned to adjust rising edges in the output clock signal **740**. The level of current flowing through the PMOS transistors **734a** and **736a** may be used to tune the delay between the complementary input clock signal **710b** and the output clock signal **740**.

(69) The output **730a** of the first tracking circuit **706a** is coupled to an input of the first output driver circuit **704a**. In the illustrated example, a second NMOS output transistor **728a** has a gate that is coupled to the drain of the input NMOS transistor **732a**, a drain that is coupled to VDD, and a source that is coupled to the output clock signal **740**.

(70) The second tracking circuit **706b** includes an input PMOS transistor **732b** coupled in series with two NMOS transistors **734b**, **736b** between the rails of a power supply (VDD and ground in FIG. 7). The input PMOS transistor **732b** has a source coupled to VDD and a gate that is coupled to the complementary input clock signal **710b**. The drain of the input PMOS transistor **732b** provides the output **730ba** of the second tracking circuit **706b**. The drain of input PMOS transistor **732b** is coupled to ground through two series coupled NMOS transistors **734b** and **736b**, of which at least NMOS transistor **736b** is tunable. The gates of the NMOS transistors **734b** and **736b** receive respective bias voltages **742** and **744** that can be configured to control the amplitude of current flowing from the source of NMOS transistor **734b** to ground through NMOS transistor **736b**. In one example, NMOS transistor **736b** may be constructed using multiple NMOS transistors that can be coupled in parallel. A tuning code may control switches that select or activate a quantity of NMOS transistors or individual NMOS transistors to be coupled in parallel. The bias voltage **744** is coupled to the base of at least the selected or activated NMOS transistors. In another example, NMOS transistor **736b** may be tuned using an analog control signal. NMOS transistor **736b** may be used to tune the amplitude of current flowing from the source of NMOS transistor **734b** to ground.

(71) The bias voltages **742** and **744** provided to the gates of NMOS transistors **734b** and **736b**, respectively, may be generated using a bandgap reference current (I_e). The bias voltages **742** and **744** control the level of current that flows through NMOS transistors **734b** and **736b** to ground, and the NMOS transistors **734b** and **736b** may be characterized as a current source or an I_e current source. The level of current flowing through the NMOS transistors **734b** and **736b** can be controlled, calibrated or tuned to adjust falling edges in the output clock signal **740**. The level of

current flowing through the NMOS transistors **734b** and **736b** may be used to tune the delay between the complementary input clock signal **710b** and the output clock signal **740**.

(72) The output **730b** of the second tracking circuit **706b** is coupled to an input of the second output driver circuit **704b**. In the illustrated example, a second PMOS output transistor **728b** has a gate that is coupled to the drain of the input PMOS transistor **732b**, a drain that is coupled to ground, and a source that is coupled to the output clock signal **740**.

(73) The illustrated delay cell **700** includes a DCC circuit **708** that provides duty cycle correction in addition to the DCC circuit **622** provided in the hybrid clock generation circuit **600** illustrated in FIG. 6. In the illustrated delay cell **700**, the transition times of rising and/or falling edges in a clock signal are modified to obtain a desired delay duration. The duty cycle of the clock signal may be changed when rising edges and falling edges have different transition times after the delay cell **700** has been calibrated or configured. While the external DCC circuit **622** may be used in some implementations to compensate for duty cycle distortion within the delay cell **700**, race conditions can occur because calibration of the DCC circuit **622** and calibration of the delay cell **700** are performed independently of one another, and the calibration processes can counteract each other without producing a desired configuration of both the DCC circuit **622** and the delay cell **700**. The use of the internal DCC circuit **708** can correct duty cycle distortions introduced by the configuration of the delay cell **700** without modifying the configuration of the external DCC circuit **622**.

(74) The illustrated DCC circuit **708** includes an NMOS transistor **722** and a tunable PMOS transistor **724**. In other examples, the NMOS transistor **722** may be tunable in addition or as an alternative to the tunable PMOS transistor **724**. The NMOS transistor **722** has a source coupled to ground and a gate that is configured to receive the bias voltage **744**. The drain of NMOS transistor **722** is coupled to the source of NMOS transistor **714a** in the first input circuit **702a**. The PMOS transistor **724** has a source coupled to VDD and a drain that is coupled to the source of PMOS transistor **714b** in the second input circuit **702b**. The gate of PMOS transistor **724** receives the bias voltage **746** and may be configured to control the amplitude of current flowing from VDD through PMOS transistor **724**. In one example, PMOS transistor **724** may be constructed using multiple PMOS transistors that can be coupled in parallel. A tuning code may control switches that select or activate a quantity of PMOS transistors or individual PMOS transistors to be coupled in parallel. The bias voltage **746** is coupled to the base of at least the selected or activated PMOS transistors. In another example, PMOS transistor **724** may be tuned using an analog control signal.

(75) The currents provided to the input circuits **702a** and **702b** by the DCC circuit **708** can be configured to tune or further adjust the transition times of edges in the input clock signal **710a** by the input circuits **702a** and **702b** in order to correct or offset duty cycle distortions generated within the delay cell **700**. In certain implementations, the timing of rising edges in the output clock signal **740** can be tuned at the first input circuit **702a** using the current flowing through NMOS transistor **722** and the timing of falling edges in the output clock signal **740** can be tuned at the first input circuit **702a** using the current flowing through PMOS transistor **724**. In the illustrated example, the timing of falling edges in the output clock signal **740** may be tuned by varying current flow through the PMOS transistor **724** while the current flowing through NMOS transistor **722** remains constant. In other examples, the timing of falling edges in the output clock signal **740** may be tuned by varying the current flowing through NMOS transistor **722** while the current flowing through PMOS transistor **724** remains constant.

(76) FIG. 8 illustrates certain aspects of the response **800** of the main delay generation section **810** to a rising edge in the input clock signal **710a**. A transition to a high voltage level on the input clock signal **710a** deactivates, disables or turns off the input PMOS transistor **712a** causing the voltage at the output **720a** of the first input circuit **702a** to be pulled to a low voltage level through the operation **802** of the NMOS transistors **714a**, **716a**. For the purposes of this description, the low voltage level may be substantially equal to the ground voltage level and the high voltage level may

approach VDD and, in any case, is greater than the low voltage level. The low voltage level of the output **720a** of the first input circuit **702a** causes the first PMOS output transistor **726a** in the first output driver circuit **704a** to be activated, enabled or turned on. The first PMOS output transistor **726a** causes **804** the output clock signal **740** to transition to the high voltage level when activated, enabled or turned on. The second output driver circuit **704b** is deactivated, disabled or turned off when the input clock signal **710a** transitions to the high voltage level.

(77) FIG. **9** illustrates certain aspects of the response **900** of the main delay generation section **810** to a falling edge in the input clock signal **710a**. A transition to a low voltage level on the input clock signal **710a** deactivates, disables or turns off the input NMOS transistor **712b** causing the voltage at the output **720b** of the second input circuit **702b** to be pulled to a high voltage level through the operation **902** of the PMOS transistors **714b**, **716b**. The high voltage level of the output **720b** of the second input circuit **702b** causes the first NMOS output transistor **726b** in the second output driver circuit **704b** to be activated, enabled or turned on. The first NMOS output transistor **726b** causes **904** the output clock signal **740** to transition to the low voltage level when activated, enabled or turned on. The first output driver circuit **704a** is deactivated, disabled or turned off when the input clock signal **710a** transitions to the low voltage level.

(78) FIG. **10** illustrates certain aspects of the response **1000** of the compensation section **1010** to a rising edge in the input clock signal **710a**. As discussed in reference to FIG. **9**, a transition to a high voltage level on the input clock signal **710a** deactivates, disables or turns off the input PMOS transistor **712a** causing the voltage at the output **720a** of the first input circuit **702a** to be pulled to a low voltage level through the operation **802** of the NMOS transistors **714a**, **716a**. The low voltage level of the output **720a** of the first input circuit **702a** causes the first PMOS output transistor **726a** in the first output driver circuit **704a** to be activated, enabled or turned on. The first PMOS output transistor **726a** causes **804** the output clock signal **740** to transition to the high voltage level when activated, enabled or turned on. The second output driver circuit **704b** is deactivated, disabled or turned off when the input clock signal **710a** transitions to the high voltage level.

(79) The first tracking circuit **706a** also drives the output clock signal **740** to the high voltage level when a rising edge is provided in the input clock signal **710a**. The first tracking circuit **706a** provides cross-skew corner compensation for the first PMOS output transistor **726a**. The first tracking circuit **706a** responds to the complementary input clock signal **710b**, and a transition to the low voltage level on the complementary input clock signal **710b** deactivates, disables or turns off the input NMOS transistor **732a**, causing the voltage at the output **730a** of the first tracking circuit **706a** to be pulled to a high voltage level through the operation **1002** of the PMOS transistors **734a**, **736a**. The high voltage level of the output **720a** of the first tracking circuit **706a** causes the second NMOS output transistor **728a** in the first output driver circuit **704a** to be activated, enabled or turned on. The second NMOS output transistor **728a** further causes **1004** the output clock signal **740** to transition to the high voltage level when activated, enabled or turned on.

(80) FIG. **11** illustrates certain aspects of the response **1100** of the compensation section **1010** to a falling edge in input clock signal **710a**. As discussed in reference to FIG. **9**, a transition to a low voltage level on the input clock signal **710a** deactivates, disables or turns off the input NMOS transistor **712b** causing the voltage at the output **720b** of the second input circuit **702b** to be pulled to a high voltage level through the operation **902** of the PMOS transistors **714b**, **716b**. The high voltage level of the output **720b** of the second input circuit **702b** causes the first NMOS output transistor **726b** in the second output driver circuit **704b** to be activated, enabled or turned on. The first NMOS output transistor **726b** causes **904** the output clock signal **740** to transition to the low voltage level. The first input circuit **702a** and the first output driver circuit **704a** are deactivated, disabled or turned off when the input clock signal **710a** transitions to the low voltage level.

(81) The second tracking circuit **706b** also drives the output clock signal **740** to the low voltage level when a falling edge is provided in the input clock signal **710a**. The second tracking circuit **706b** provides cross-skew corner compensation for the first NMOS output transistor **726b**. The

second tracking circuit **706b** responds to the complementary input clock signal **710b**, and a transition to the high voltage level on the complementary input clock signal **710b** deactivates, disables or turns off the input PMOS transistor **732b**, causing the voltage at the output **730b** of second tracking circuit **706b** to be pulled to a low voltage level through the operation **1102** of the NMOS transistors **734b**, **736b**. The low voltage level of the output **720b** of the second tracking circuit **706b** causes the second PMOS output transistor **728b** in the second output driver circuit **704b** to be activated, enabled or turned on. The second PMOS output transistor **728b** further causes **1104** the output clock signal **740** to transition to the high voltage level when activated, enabled or turned on.

(82) FIG. **12** illustrates examples of signaling **1200** and **1220** configured or adapted in accordance with certain aspects of this disclosure. The configuration of the clock signals may correspond in certain respects to the configuration of the multiphase signal provided as the multiphase output **620** of the hybrid clock generation circuit **600** illustrated in FIG. **6**. The first example corresponds to signaling **1200** obtained when the clock generation circuit is operating with nominal timing. The signaling **1200** include an in-phase version of a clock signal (the I phase **1202**), a quadrature version of the clock signal (the Q phase **1204**) that is phase-shifted by 90° from the I phase **1202**, an inverse version of the I phase **1202** (the Ib phase **1206**) that is phase-shifted by 180° from the I phase **1202** and an inverse version of the Q phase **1204** (the Qb phase **1208**) that is phase-shifted by 180° from the Q phase **1204**. The edges in these phases **1202**, **1204**, **1206** and **1208** define four portions of each clock cycle **1210**, as indicated by the phase state indicators **1212**, **1214**, **1216**, **1218**. The durations of the pulses in the phase state indicators **1212**, **1214**, **1216**, **1218** are equal for a nominally operating clock generation circuit.

(83) The second example corresponds to signaling **1220** with a distorted duty cycle. The signaling **1220** has the same frequency as the signaling **1200** illustrated in the first example. The signaling **1220** includes an in-phase version of the clock signal (the I phase **1222**), a quadrature version of the clock signal (the Q phase **1224**) that is phase-shifted by 90° from the I phase **1222**, an inverse version of the I phase **1222** (the Ib phase **1226**) that is phase-shifted by 180° from the I phase **1222** and an inverse version of the Q phase **1224** (the Qb phase **1228**) that is phase-shifted by 180° from the Q phase **1224**. In this example, duty cycle distortion affects the Q phase **1224** and the Qb phase **1228**. In some instances, duty cycle distortions affect some other combination of the phases **1222**, **1224**, **1226** and **1228**. In some instances, duty cycle distortions affect all of the phases **1222**, **1224**, **1226** and **1228**. The combination of phases **1222**, **1224**, **1226** and **1228** affected by duty cycle distortion is based on the source of the distortion. The edges in these phases **1222**, **1224**, **1226** and **1228** define four portions of each clock cycle **1210**, as indicated by the phase state indicators **1232**, **1234**, **1236**, **1238**. In the illustrated example, the duration of pulses in one phase state indicator **1236** is different from the durations of pulses in the other phase state indicators **1232**, **1234**, **1238**. The duration of the state indicator **1236** includes an additional delay **1230** that distorts the duty cycle of the Q phase **1224** and the Qb phase **1228**.

(84) Referring also to the hybrid clock generation circuit **600** illustrated in FIG. **6** and the delay cell **700** illustrated in FIG. **7**, a sequence of calibration or configuration steps may be followed to obtain a multiphase clock signal in which each phase **1202**, **1204**, **1206**, **1208** has a desired frequency and duty cycle. The frequency of the input clock signal **610** may be configured or calibrated as an initial step. The DCC circuit **612** or **622** may then be configured or calibrated to provide a corrected clock signal **616** or **626** with a 50% duty cycle.

(85) One or more calibration steps may be performed for the delay module **614** in the half-rate path **602**. In the example of a delay cell **700** illustrated in FIG. **7**, the delays provided by the delay cell **700** may be calibrated by configuring the bias voltages **742** and **744**. The delays may be tuned by configuring the tunable transistors **716a**, **716b**, **736a** and **736b**. Duty cycle distortions may be corrected by calibrating or configuring the DCC circuit **708**. In one example, the timing of falling edges in the output clock signal **740** may be tuned by varying current flow through the PMOS

transistor **724** while the current flowing through NMOS transistor **722** remains constant. In another example, the timing of falling edges in the output clock signal **740** may be tuned by varying the current flowing through NMOS transistor **722** while the current flowing through PMOS transistor **724** remains constant.

(86) The divider circuit **624** in the full-rate path **604** may require little or no calibration and configuration. In some implementations, the CMOS circuits used to construct the divider circuit **624** can provide a divider that is simple and robust in the presence of PVT variations. A divider circuit **624** constructed from CMOS circuits can be expected to operate at low power may be easily scaled with improvements or changes in process technology.

(87) FIG. **13** illustrates an example of a divider circuit **1300** that may be used in the full-rate path **604** of the hybrid clock generation circuit **600** illustrated in FIG. **6**. In the illustrated example, a first divide-by-2 divider **1302** receives an input clock signal **1308** and produces an in-phase output signal (the I phase **1312**) and an inverted version of the I phase **1312** (the Ib phase **1316**) that is phase-shifted by 180° from the I phase **1312**. The input clock signal **1308** is provided to an inverter **1306** that provides an inverted input clock signal **1310** to a second divide-by-2 divider **1304**. The second divide-by-2 divider **1304** produces a quadrature version of the output signal (the Q phase **1314**) that is phase-shifted by 90° from the I phase **1312**, and an inverted version of the Q phase **1314** (the Qb phase **1318**) that is phase-shifted by 180° from the Q phase **1204**.

(88) The timing diagram **1320** illustrates the expected relationships between the input clock signal **1308**, the inverted input clock signal **1310**, the I phase **1312**, the Q phase **1314**, the Ib phase **1316** and the Qb phase **1318**. In one example, the input clock signal **1308** has a frequency of 12 GHz, and produces an output clock in four phases **1312**, **1314**, **1316** and **1318** at a frequency of 6 GHz.

(89) FIG. **13** also illustrates one example in which each of the divide-by-2 dividers **1302**, **1304** may be implemented using a D-Flipflop (the DFF **1330**). The example of a D-Flipflop is provided solely to facilitate this description, and other types of divider circuit, flipflops, registers or set-reset circuits may be combined or employed to construct the divider circuit **624** in the full-rate path **604** illustrated in FIG. **6**. The illustrated DFF **1330** may be triggered by a rising edge or falling edge in a clock signal **1332** and is configured to toggle its output **1334** when triggered.

(90) FIG. **14** is a flowchart **1400** of a method for generating clock signals in accordance with certain aspects of this disclosure. The method may be performed using a clock generation circuit such as the hybrid clock generation circuit **600** illustrated in FIG. **6**. In some instances, the method may be implemented or involve using one or more processors or controllers. At block **1402** in the illustrated method, an input clock signal may be divided to obtain a first in-phase output clock signal. At block **1404** in the illustrated method, an inverted version of the input clock signal may be divided to obtain a first quadrature output clock signal. The first quadrature output clock signal may be a quadrature version of the first in-phase output clock signal. The first in-phase output clock signal and the first quadrature output clock signal may be included in a full-rate output. The full-rate output may include one or more multiphase signals.

(91) At block **1406** in the illustrated method, edges in the input clock signal may be delayed to obtain a second quadrature output clock signal. The second quadrature output clock signal being a quadrature version of the input clock signal. The quadrature output clock signal may be included in a half-rate output. The half-rate output may include one or more multiphase signals. In one example, an inverted version of the second quadrature output clock signal is included in the half-rate output.

(92) At block **1408** in the illustrated method, a multiplexer may select the full-rate output to provide the multiphase output clock in a first mode of operation. At block **1410** in the illustrated method, the multiplexer may select the half-rate output to provide the multiphase output clock in a second mode of operation. In some instances, an inverted version of the first in-phase output clock signal and an inverted version of the first quadrature output clock signal are included in the full-rate output.

(93) In some implementations, a second in-phase output clock signal may be provided in the half-rate output. The second in-phase output clock signal may include an in-phase version of the input clock signal. In some of these implementations, an inverted version of the second in-phase output clock signal may be included in the half-rate output. A first tracking circuit may be used to provide cross-skew compensation to rising edges in the second in-phase output clock signal. The structure and operation of the first tracking circuit may correspond in some respects to the structure and operation of the first tracking circuit **706a** in the delay cell **700** illustrated in FIGS. **7-11**. A second tracking circuit may be used to provide cross-skew compensation to falling edges in the second in-phase output clock signal. The structure and operation of the second tracking circuit may correspond in some respects to the structure and operation of the second tracking circuit **706b** in the delay cell **700** illustrated in FIGS. **7-11**.

(94) In some examples, a first duty cycle correction circuit is used to decouple the input clock signal from a delay circuit that is configured to provide the second quadrature output clock signal in the first mode of operation. A second duty cycle correction circuit may be used to correct duty cycle distortions caused by the delay cell. In some examples, a third duty cycle correction circuit is used to decouple the input clock signal from one or more divider circuits that are configured to generate the first in-phase output clock signal or the first quadrature output clock signal in the first mode of operation.

(95) The method illustrated in FIG. **11** may be executed in or using an IC device. In one example, the IC device comprises an SoC. In another example, the IC device is included in one of multiple semiconductor dice mounted on a substrate. The IC device may be implemented as a chiplet in some instances.

(96) The IC device may include a bus interface. The bus interface may include a hybrid clock generation circuit that has a divider circuit as part of a full-rate path for clock distribution, a delay cell as part of a half-rate path for clock distribution, and a multiplexer that can be commanded or controlled to select between the full-rate path and the half-rate path. The divider circuit includes a first divider and a second divider. The first divider may be coupled to an input clock signal. The first divider may be configured to provide a first in-phase output clock signal in a full-rate output. The first in-phase output clock signal may have a frequency that is half the frequency of the input clock signal. The second divider may be coupled to an inverted version of the input clock signal. The second divider may be configured to provide a first quadrature output clock signal in the full-rate output. The first quadrature output clock signal may be a quadrature version of the first in-phase output clock signal. The delay cell can be configured to delay edges in the input clock signal and to provide a half-rate output. The half-rate output includes a second quadrature output clock signal that is a quadrature version of the input clock signal. The multiplexer may be configured to select the full-rate output to provide a multiphase output clock when the hybrid clock generation circuit is configured for a first mode of operation. The multiplexer may be configured to select the half-rate output to provide the multiphase output clock when the hybrid clock generation circuit is configured for a second mode of operation.

(97) In some implementations, the first divider is further configured to provide an inverted version of the first in-phase output clock signal in the full-rate output. The second divider may be further configured to provide an inverted version of the first quadrature output clock signal in the full-rate output.

(98) In certain implementations, the delay cell is configured to provide a second in-phase output clock signal in the half-rate output. The second in-phase output clock signal may be an in-phase version of the input clock signal. The delay cell may be configured to provide an inverted version of the second in-phase output clock signal in the half-rate output. The delay cell may include a compensation section. In the compensation section, a first tracking circuit may be configured to provide cross-skew compensation to rising edges in the second in-phase output clock signal, and a second tracking circuit may be configured to provide cross-skew compensation to falling edges in

the second in-phase output clock signal.

(99) In some implementations, the delay cell is configured to provide an inverted version of the second quadrature output clock signal in the half-rate output. The delay cell may be configured to receive the input clock signal through a first duty cycle correction circuit. The first duty cycle correction circuit may be configured to decouple the delay cell from the input clock signal when the hybrid clock generation circuit is configured for the first mode of operation. The delay cell may have a second duty cycle correction circuit configured to correct duty cycle distortions caused by the delay cell.

(100) The first divider and the second divider may be configured to receive the input clock signal through a third duty cycle correction circuit. The third duty cycle correction circuit may be configured to decouple the first divider and the second divider from the input clock signal when the hybrid clock generation circuit is configured for the second mode of operation.

(101) Some implementation examples are described in the following numbered clauses:

(102) 1. A hybrid clock generation circuit, comprising: a divider circuit that comprises: a first divider coupled to an input clock signal and configured to provide a first in-phase output clock signal in a full-rate output, the first in-phase output clock signal having a frequency that is half the frequency of the input clock signal; and a second divider coupled to an inverted version of the input clock signal and configured to provide a first quadrature output clock signal in the full-rate output, the first quadrature output clock signal being a quadrature version of the first in-phase output clock signal; a delay cell configured to delay edges in the input clock signal and to provide a half-rate output comprising a second quadrature output clock signal that is a quadrature version of the input clock signal; and a multiplexer configured to: select the full-rate output to provide a multiphase output clock when the hybrid clock generation circuit is configured for a first mode of operation; and select the half-rate output to provide the multiphase output clock when the hybrid clock generation circuit is configured for a second mode of operation.

(103) 2. The hybrid clock generation circuit as described in clause 1, wherein the first divider is further configured to provide an inverted version of the first in-phase output clock signal in the full-rate output, and wherein the second divider is further configured to provide an inverted version of the first quadrature output clock signal in the full-rate output.

(104) 3. The hybrid clock generation circuit as described in clause 1 or clause 2, wherein the delay cell is configured to provide a second in-phase output clock signal in the half-rate output, the second in-phase output clock signal being an in-phase version of the input clock signal.

(105) 4. The hybrid clock generation circuit as described in clause 3, wherein the delay cell is configured to provide an inverted version of the second in-phase output clock signal in the half-rate output.

(106) 5. The hybrid clock generation circuit as described in clause 3 or clause 4, wherein the delay cell comprises: a first tracking circuit that is configured to provide cross-skew compensation to rising edges in the second in-phase output clock signal; and a second tracking circuit that is configured to provide cross-skew compensation to falling edges in the second in-phase output clock signal.

(107) 6. The hybrid clock generation circuit as described in any of clauses 1-5, wherein the delay cell is configured to provide an inverted version of the second quadrature output clock signal in the half-rate output.

(108) 7. The hybrid clock generation circuit as described in any of clauses 1-6, wherein the delay cell is configured to receive the input clock signal through a first duty cycle correction circuit, wherein the first duty cycle correction circuit is configured to decouple the delay cell from the input clock signal when the hybrid clock generation circuit is configured for the first mode of operation.

(109) 8. The hybrid clock generation circuit as described in any of clauses 1-7, wherein the delay cell comprises: a second duty cycle correction circuit configured to correct duty cycle distortions

caused by the delay cell.

(110) 9. The hybrid clock generation circuit as described in any of clauses 1-8, wherein the first divider and the second divider are configured to receive the input clock signal through a third duty cycle correction circuit, wherein the third duty cycle correction circuit is configured to decouple the first divider and the second divider from the input clock signal when the hybrid clock generation circuit is configured for the second mode of operation.

(111) 10. A method for generating clock signals, comprising: dividing an input clock signal to obtain a first in-phase output clock signal; dividing an inverted version of the input clock signal to obtain a first quadrature output clock signal, the first quadrature output clock signal being a quadrature version of the first in-phase output clock signal, wherein the first in-phase output clock signal and the first quadrature output clock signal are included in a full-rate output; delaying edges in the input clock signal to obtain a second quadrature output clock signal, the second quadrature output clock signal being a quadrature version of the input clock signal, wherein the second quadrature output clock signal is included in a half-rate output; and selecting the full-rate output to provide a multiphase output clock in a first mode of operation; and selecting the half-rate output to provide the multiphase output clock in a second mode of operation.

(112) 11. The method as described in clause 10, further comprising: providing an inverted version of the first in-phase output clock signal in the full-rate output; and providing an inverted version of the first quadrature output clock signal in the full-rate output.

(113) 12. The method as described in clause 10 or clause 11, further comprising: providing a second in-phase output clock signal in the half-rate output, the second in-phase output clock signal being an in-phase version of the input clock signal.

(114) 13. The method as described in clause 12, further comprising: providing an inverted version of the second in-phase output clock signal in the half-rate output.

(115) 14. The method as described in clause 12 or clause 13, further comprising: using a first tracking circuit to provide cross-skew compensation to rising edges in the second in-phase output clock signal; and using a second tracking circuit to provide cross-skew compensation to falling edges in the second in-phase output clock signal.

(116) 15. The method as described in any of clauses 10-14, further comprising: providing an inverted version of the second quadrature output clock signal in the half-rate output.

(117) 16. The method as described in any of clauses 10-15, further comprising: using a first duty cycle correction circuit to decouple the input clock signal from a delay circuit that is configured to provide the second quadrature output clock signal in the first mode of operation.

(118) 17. The method as described in any of clauses 10-16, further comprising: using a delay cell to delay the edges in the input clock signal; and using a second duty cycle correction circuit to correct duty cycle distortions caused by the delay cell.

(119) 18. The method as described in any of clauses 10-17, further comprising: using a third duty cycle correction circuit to decouple the input clock signal from one or more divider circuits that are configured to generate the first in-phase output clock signal or the first quadrature output clock signal in the first mode of operation.

(120) 19. An apparatus, comprising: means for dividing an input clock signal, including a first divider that is configured to provide a first in-phase output clock signal in a full-rate output, the first in-phase output clock signal having a frequency that is half the frequency of the input clock signal, and a second divider that is configured to provide a first quadrature output clock signal in the full-rate output, the first quadrature output clock signal being a quadrature version of the first in-phase output clock signal; means for delaying edges in the input clock signal, including a delay cell that is configured to provide a second quadrature output clock signal in a half-rate output, the second quadrature output clock signal being a quadrature version of the input clock signal; and means for providing a multiphase output clock, including a multiplexer that is configured to select the full-rate output to provide the multiphase output clock in a first mode of operation, and select

the half-rate output to provide the multiphase output clock in a second mode of operation.

(121) 20. The apparatus as described in clause 19, wherein the first divider is further configured to provide an inverted version of the first in-phase output clock signal in the full-rate output, and wherein the second divider is further configured to provide an inverted version of the first quadrature output clock signal in the full-rate output.

(122) 21. The apparatus as described in clause 19 or clause 20, wherein the delay cell is configured to provide a second in-phase output clock signal in the half-rate output, the second in-phase output clock signal being an in-phase version of the input clock signal.

(123) 22. The apparatus as described in clause 21, wherein the delay cell is configured to provide an inverted version of the second in-phase output clock signal in the half-rate output.

(124) 23. The apparatus as described in clause 21 or clause 22, wherein the delay cell comprises: a first tracking circuit configured to provide cross-skew compensation to rising edges in the second in-phase output clock signal; and a second tracking circuit configured to provide cross-skew compensation to falling edges in the second in-phase output clock signal.

(125) 24. The apparatus as described in any of clauses 19-23, wherein the delay cell is configured to provide an inverted version of the second quadrature output clock signal in the half-rate output.

(126) 25. The apparatus as described in any of clauses 19-24, wherein the delay cell is configured to receive the input clock signal through a first duty cycle correction circuit, wherein the first duty cycle correction circuit is configured to decouple the delay cell from the input clock signal in the first mode of operation.

(127) 26. The apparatus as described in any of clauses 19-25, wherein the delay cell comprises: a second duty cycle correction circuit configured to correct duty cycle distortions caused by the delay cell.

(128) 27. The apparatus as described in any of clauses 19-26, wherein the delay cell comprises: a third duty cycle correction circuit configured to decouple the input clock signal from one or more divider circuits that are configured to generate the first in-phase output clock signal or the first quadrature output clock signal in the first mode of operation.

(129) It is understood that the specific order or hierarchy of steps in the processes disclosed is an illustration of exemplary approaches. Based upon design preferences, it is understood that the specific order or hierarchy of steps in the processes may be rearranged. Further, some steps may be combined or omitted. The accompanying method claims present elements of the various steps in a sample order, and are not meant to be limited to the specific order or hierarchy presented.

(130) The previous description is provided to enable any person skilled in the art to practice the various aspects described herein. Various modifications to these aspects will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other aspects. Thus, the claims are not intended to be limited to the aspects shown herein, but is to be accorded the full scope consistent with the language claims, wherein reference to an element in the singular is not intended to mean “one and only one” unless specifically so stated, but rather “one or more.” Unless specifically stated otherwise, the term “some” refers to one or more. All structural and functional equivalents to the elements of the various aspects described throughout this disclosure that are known or later come to be known to those of ordinary skill in the art are expressly incorporated herein by reference and are intended to be encompassed by the claims. Moreover, nothing disclosed herein is intended to be dedicated to the public regardless of whether such disclosure is explicitly recited in the claims. No claim element is to be construed as a means plus function unless the element is expressly recited using the phrase “means for.”

Claims

1. A hybrid clock generation circuit, comprising: a divider circuit that comprises: a first divider coupled to an input clock signal and configured to provide a first in-phase output clock signal in a

full-rate output, the first in-phase output clock signal having a frequency that is half the frequency of the input clock signal; and a second divider coupled to an inverted version of the input clock signal and configured to provide a first quadrature output clock signal in the full-rate output, the first quadrature output clock signal being a quadrature version of the first in-phase output clock signal; a delay cell configured to delay edges in the input clock signal and to provide a half-rate output comprising a second quadrature output clock signal that is a quadrature version of the input clock signal; and a multiplexer configured to: select the full-rate output to provide a multiphase output clock when the hybrid clock generation circuit is configured for a first mode of operation; and select the half-rate output to provide the multiphase output clock when the hybrid clock generation circuit is configured for a second mode of operation.

2. The hybrid clock generation circuit of claim 1, wherein the first divider is further configured to provide an inverted version of the first in-phase output clock signal in the full-rate output, and wherein the second divider is further configured to provide an inverted version of the first quadrature output clock signal in the full-rate output.

3. The hybrid clock generation circuit of claim 1, wherein the delay cell is configured to provide a second in-phase output clock signal in the half-rate output, the second in-phase output clock signal being an in-phase version of the input clock signal.

4. The hybrid clock generation circuit of claim 3, wherein the delay cell is configured to provide an inverted version of the second in-phase output clock signal in the half-rate output.

5. The hybrid clock generation circuit of claim 3, wherein the delay cell comprises: a first tracking circuit that is configured to provide cross-skew compensation to rising edges in the second in-phase output clock signal; and a second tracking circuit that is configured to provide cross-skew compensation to falling edges in the second in-phase output clock signal.

6. The hybrid clock generation circuit of claim 1, wherein the delay cell is configured to provide an inverted version of the second quadrature output clock signal in the half-rate output.

7. The hybrid clock generation circuit of claim 1, wherein the delay cell is configured to receive the input clock signal through a first duty cycle correction circuit, wherein the first duty cycle correction circuit is configured to decouple the delay cell from the input clock signal when the hybrid clock generation circuit is configured for the first mode of operation.

8. The hybrid clock generation circuit of claim 1, wherein the delay cell comprises: a second duty cycle correction circuit configured to correct duty cycle distortions caused by the delay cell.

9. The hybrid clock generation circuit of claim 1, wherein the first divider and the second divider are configured to receive the input clock signal through a third duty cycle correction circuit, wherein the third duty cycle correction circuit is configured to decouple the first divider and the second divider from the input clock signal when the hybrid clock generation circuit is configured for the second mode of operation.

10. A method for generating clock signals, comprising: dividing an input clock signal to obtain a first in-phase output clock signal; dividing an inverted version of the input clock signal to obtain a first quadrature output clock signal, the first quadrature output clock signal being a quadrature version of the first in-phase output clock signal, wherein the first in-phase output clock signal and the first quadrature output clock signal are included in a full-rate output; delaying edges in the input clock signal to obtain a second quadrature output clock signal, the second quadrature output clock signal being a quadrature version of the input clock signal, wherein the second quadrature output clock signal is included in a half-rate output; selecting the full-rate output to provide a multiphase output clock in a first mode of operation; and selecting the half-rate output to provide the multiphase output clock in a second mode of operation.

11. The method of claim 10, further comprising: providing an inverted version of the first in-phase output clock signal in the full-rate output; and providing an inverted version of the first quadrature output clock signal in the full-rate output.

12. The method of claim 10, further comprising: providing a second in-phase output clock signal in

the half-rate output, the second in-phase output clock signal being an in-phase version of the input clock signal.

13. The method of claim 12, further comprising: providing an inverted version of the second in-phase output clock signal in the half-rate output.

14. The method of claim 12, further comprising: using a first tracking circuit to provide cross-skew compensation to rising edges in the second in-phase output clock signal; and using a second tracking circuit to provide cross-skew compensation to falling edges in the second in-phase output clock signal.

15. The method of claim 10, further comprising: providing an inverted version of the second quadrature output clock signal in the half-rate output.

16. The method of claim 10, further comprising: using a first duty cycle correction circuit to decouple the input clock signal from a delay circuit that is configured to provide the second quadrature output clock signal in the first mode of operation.

17. The method of claim 10, further comprising: using a delay cell to delay the edges in the input clock signal; and using a second duty cycle correction circuit to correct duty cycle distortions caused by the delay cell.

18. The method of claim 10, further comprising: using a third duty cycle correction circuit to decouple the input clock signal from one or more divider circuits that are configured to generate the first in-phase output clock signal or the first quadrature output clock signal in the first mode of operation.

19. An apparatus, comprising: means for dividing an input clock signal, including a first divider that is configured to provide a first in-phase output clock signal in a full-rate output, the first in-phase output clock signal having a frequency that is half the frequency of the input clock signal, and a second divider that is configured to provide a first quadrature output clock signal in the full-rate output, the first quadrature output clock signal being a quadrature version of the first in-phase output clock signal; means for delaying edges in the input clock signal, including a delay cell that is configured to provide a second quadrature output clock signal in a half-rate output, the second quadrature output clock signal being a quadrature version of the input clock signal; and means for providing a multiphase output clock, including a multiplexer that is configured to select the full-rate output to provide the multiphase output clock in a first mode of operation, and select the half-rate output to provide the multiphase output clock in a second mode of operation.

20. The apparatus of claim 19, wherein the first divider is further configured to provide an inverted version of the first in-phase output clock signal in the full-rate output, and wherein the second divider is further configured to provide an inverted version of the first quadrature output clock signal in the full-rate output.

21. The apparatus of claim 19, wherein the delay cell is configured to provide a second in-phase output clock signal in the half-rate output, the second in-phase output clock signal being an in-phase version of the input clock signal.

22. The apparatus of claim 21, wherein the delay cell is configured to provide an inverted version of the second in-phase output clock signal in the half-rate output.

23. The apparatus of claim 21, wherein the delay cell comprises: a first tracking circuit configured to provide cross-skew compensation to rising edges in the second in-phase output clock signal; and a second tracking circuit configured to provide cross-skew compensation to falling edges in the second in-phase output clock signal.

24. The apparatus of claim 19, wherein the delay cell is configured to provide an inverted version of the second quadrature output clock signal in the half-rate output.

25. The apparatus of claim 19, wherein the delay cell is configured to receive the input clock signal through a first duty cycle correction circuit, wherein the first duty cycle correction circuit is configured to decouple the delay cell from the input clock signal in the first mode of operation.

26. The apparatus of claim 19, wherein the delay cell comprises: a second duty cycle correction

circuit configured to correct duty cycle distortions caused by the delay cell.

27. The apparatus of claim 19, wherein the delay cell comprises: a third duty cycle correction circuit configured to decouple the input clock signal from one or more divider circuits that are configured to generate the first in-phase output clock signal or the first quadrature output clock signal in the first mode of operation.
