

CURRENT MIRROR COMPENSATION
USING CHANNEL LENGTH MODULATION

TECHNICAL FIELD

5 The circuitry described herein relates generally to automatic test equipment, and more particularly low jitter timing generation circuits for automatic test equipment applications.

BACKGROUND

10 Timing edge placement is often a critical parameter for high performance semiconductor testers. Having the ability to place the rising and/or falling edge of a test signal within a few picoseconds of a desired point in time may mean the difference in passing or failing large numbers of semiconductor devices under test.

 Conventional timing generators that produce high accuracy timing signals are
15 often employed in CMOS integrated circuits. CMOS technology provides relatively good performance at very low cost. However, CMOS ICs are often susceptible to temperature and other conditions that affect the performance of the circuit. To counter this, many CMOS timing generators employ sophisticated compensation techniques to minimize changes in delay.

20 With reference to Figure 1, a conventional CMOS timing generator 10 that provides for temperature compensation typically includes a plurality of delay elements D1 - DN coupled together to form a delay line. Each of the delay element outputs serve as timing selection inputs to a timing signal selector (not shown). The same outputs are also used for a delay compensation scheme. A compensation multiplexer
25 12 is employed, that receives the delay outputs, and provides an output to a phase detector 14, where it is compared to a reference signal Vref to determine any phase difference. A compensation voltage is then generated in response to the magnitude of any phase difference, and fed to a charge pump or voltage-to-current converter 16. The current generated by the converter is provided as a reference bias current to a bias
30 current fanout circuit 18 that duplicates and distributes bias current to the delay elements to control the delay.

 To fanout, or distribute the bias current to the various delay elements, a current mirror circuit scheme is typically employed. As shown in Figure 2, a conventional
35 current mirror includes a reference current source 19 coupled to a current source transistor QS to generate the same current through a first mirror transistor QFM. The mirror transistor's gate is tied to its drain, with its source terminal coupled to the supply voltage VDD. A plurality of mirroring transistors QFM2 - QFMN are disposed

in parallel, each with its gate tied to the first mirror transistor gate, and source terminals tied to VDD.

While this configuration works well for its intended applications, the current through each mirror transistor may be susceptible to noise components acting on the VDD bus. Even a relatively small change of 100 millivolts can cause a corresponding change in the bias current through each mirror, correspondingly affecting the level of current provided therefrom. As voltage levels on integrated circuits continue to decrease, this problem becomes more pronounced.

What is needed and currently unavailable is a compensation circuit for use with current mirror circuits to minimize changes in current attributable to supply voltage noise. The current mirror compensation circuit described herein satisfies this need.

SUMMARY

The current mirror compensation circuit described herein provides a low-jitter solution for the generation of bias currents by one or more current mirrors. By minimizing the errors attributable to noise in the supply voltage, reduced supply voltage levels may be employed in integrated circuits with little error caused by the current mirror circuitry.

To realize the foregoing advantages, the circuit in one form comprises a current compensation circuit for use with a current mirror circuit. The current mirror circuit has a current path defined by a first programmable current mirror stage driving a first fanout current mirror stage. The first programmable current mirror stage includes at least one transistor with a channel length exhibiting a first channel length modulation factor λ_1 . The first fanout current mirror stage connects to a supply voltage source. The current compensation circuit comprises a supply voltage current mirror coupled to the supply voltage source and has a current output coupled to the current path. The compensation circuit further includes a second programmable current mirror coupled in series to the supply voltage current mirror and including at least one transistor with a channel length exhibiting a channel length modulation factor λ_2 . The second channel length modulation factor λ_2 is larger than the first channel length modulation factor λ_1 . As a result, the first programmable current mirror and the second programmable current mirror cooperate to maintain a bias current through the first fanout current mirror stage substantially independent of changes in the supply voltage.

In another form, the circuit comprises a timing generator for use in a semiconductor tester. The timing generator includes a delay line having a plurality of delay cells with respective phase-shifted outputs and bias current inputs. A selector with a plurality of inputs receives the phase shifted outputs, and includes an output. Phase detection circuitry detects the phase shift between the selector output and a reference signal, and generates bias current. The timing generator further includes means for distributing the bias current to the plurality of delay cells.

Other features and advantages of the present invention will be apparent from the following detailed description when read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The circuit described herein will be better understood by reference to the following more detailed description and accompanying drawings in which

FIG. 1 is a high-level block diagram of a conventional timing generator;

5 FIG. 2 is a partial schematic view of the conventional bias current fanout circuitry employed in the timing generator of Figure 1;

FIG. 3 is a high-level block diagram of a timing generator according to one form of the circuit described herein; and

10 FIG. 4 is a high-level block diagram of a bias current source for use in the timing generator of Figure 3.

DETAILED DESCRIPTION

The current mirror compensation circuit described herein, generally designated 50, provides a unique solution for addressing the undesirable effects of a changing supply voltage in high performance CMOS timing generators. This is accomplished by feeding compensation current to bias current generated by fanout circuitry 30. The compensation current offsets any changes to the bias current resulting from any changes in VDD caused by noise or jitter. By minimizing the effects of a changing VDD, changes to the delay characteristics of the cell are also correspondingly minimized.

Referring now to Figure 3, a timing generator that employs the current mirror compensation circuit, generally designated 20, is shown. The timing generator is of the type that provides bias current compensation to control delay. The generator includes a delay line 22 comprising a set of N delay elements D1 - DN, each providing a proportional to 1/N phase offset with respect to an input clock CLK. A preferred delay element construction that provides low jitter delay is described in co-pending patent application serial number 10/376,664, titled "Low Jitter Delay Cell", filed February 28, 2003, assigned to the assignee of the present invention, and expressly incorporated by reference herein.

Further referring to Figure 3, the delay element outputs are fed to a selector, or multiplexer M1. The multiplexer output feeds a phase detector 24 that determines the phase difference between the selected delay signal (presented by the multiplexer) and a reference signal Vref. A charge pump and voltage-to-current converter 26 receives a difference signal from the phase detector to generate a reference bias current IREF. The reference bias current is then duplicated and distributed by fanout circuitry 30 to provide the bias current for the delay elements. The change in bias current serves to control the delay through each element to a desired level.

Referring now to Figure 4, the fanout circuitry 30 generally includes a reference current source input transistor QIN1 that receives an off-chip current IOC to generate a bias voltage for a first programmable current mirror PCM1. The first programmable current mirror is in the form of a current DAC, or IDAC comprising transistors QM1A - QM1N. Each of the transistors has a relatively long channel length, on the order of around 720 nanometers. As is well understood in the art, the current DAC comprises a bank of transistors that are selectively activated to achieve desired characteristics.

With continued reference to Figure 4, the first programmable current mirror PCM1 (transistor IDAC QM1A - QM1N) is disposed in series with a first fanout current mirror CM1 comprising transistor QM1, forming a node with the first programmable current mirror, at 40. While not explicitly shown in Figure 4, the voltage-to-current

converter output (Figure 3) is connected to node 40. The first fanout current mirror transistor QM1, in turn, has its gate tied to the gates of an array of mirror transistors QM2 - QMN. Because of the respective gate-to-source connections for each transistor, the current through QM1 is duplicated en masse through transistors QM2 - QMN. The duplicated currents are then fed as bias currents to the delay cells, or groups of delay cells.

For optimum control over the bias current, and to minimize the effects from undesirable changes on the supply voltage VDD, the fanout circuitry 30 includes an input, at node 40, for receiving compensation current from the current mirror compensation circuit 50.

Referring again to Figure 4, the current mirror compensation circuit 50 comprises a supply voltage detector having a supply voltage current mirror CM2 coupled to a second programmable current mirror PCM2. In the overall preferred implementation, the entire fanout and compensation circuitry is disposed on a single CMOS integrated circuit.

The supply voltage current mirror CM2 includes a diode-connected p-channel MOSFET QP1 with a source terminal coupled to the VDD supply rail. The drain terminal of transistor QP1 provides a series connection to the second programmable current mirror PCM2. A second p-channel MOSFET QP2 is configured to have a gate-to-source voltage duplicating that of QP1, thus mirroring the current, which comprises the compensation current into node 40.

The construction of the second programmable current mirror PCM2 is similar to the first programmable current mirror PCM1, but exhibits channel lengths for each transistor that are relatively short (for example, approximately 120 nanometers). In relative terms, the channel lengths for the PCM2 transistors are on the order of 1/5 the length of the PCM1 transistors. This relationship is also expressible in terms of the channel length modulation factor λ , which is higher for longer transistor channel lengths. The effect of this relative difference in modulation factor is explained more specifically below.

In operation, the accuracy of the timing generator 20 (Figure 3) depends upon the accuracy of the individual delays associated with each delay cell DN. The individual delays are each regulated by the bias current running through each cell DN. Bias current is drawn through each cell and is programmed by the user to achieve the desired delay for the cell. Generally, a higher bias current results in a shorter delay, while a lower bias current increases the delay. The bias voltage for the cell is provided by the VDD bus, generally on the order of 1.2 volts. However, noise often affects the value of VDD, sometimes increasing or decreasing the level by +/- 0.10 volts.

Where a noisy VDD affects the bias current produced by the fanout circuitry 30, the compensation current circuit 50 offsets the effect by sinking or sourcing appropriate levels of current into the input node 40 (Figure 4). In the instance where too much current is being drawn through the first fanout current mirror CM1 because of a higher supply voltage VDD due to noise, the compensation circuit 50 sources more current (due to the short channel effect) into the node 40, causing transistor QM1 to supply correspondingly less current, while the first programmable current mirror PCM1 (transistor QM1) still draws its required current. In the instance where too little current is drawn through transistor QM1, the compensation circuit sources less current, forcing QM1 to provide additional current, which is duplicated through mirror transistors QM2 - QMN. The programmability aspect of the current mirror compensation circuit allows for fine tuning the compensation current, as necessary.

During operation, the level of compensation current supplied by the compensation circuit 50 varies with the user-controlled settings of the respective programmable current mirrors PCM1 and PCM2. If a constant bias current through fanout current mirror CM1 of, for example 100 microamps, is desired, the second programmable current source can be programmed to source 400 microamps of current in response to a detected change in the supply voltage VDD. This detection results from a change in the gate-to-source voltage on the supply voltage current mirror CM2. The first programmable current source PCM1 would then be programmed to sink 500 microamps, resulting in a net required current through fanout mirror CM1 at node 40, of 100 microamps. Dynamic changes in the supply voltage VDD cause corresponding dynamic changes in the current from the respective programmable current sources PCM1 and PCM2, thus preserving a constant relative difference for duplication by the fanout circuitry 30.

Those skilled in the art will appreciate the benefits and advantages afforded by the circuit described herein. Of significant importance is the current compensation feature that offsets bias current inaccuracies caused by undesirable noise acting on the supply voltage. Further, the programmable nature of the circuit provides flexibility and accuracy in allowing for fine-tuning of the compensation current. Moreover, due to the circuit's convenient construction, it is readily adaptable for use as a standard cell block.

It will also be appreciated that the current mirror compensation circuit described herein is not limited solely to the field of automatic test equipment (ATE). While ATE presents a challenging environment where such a circuit provides a substantial beneficial impact, any application where current mirroring techniques are employed may benefit from the use of this circuit. For example, circuits that employ analog-to-digital conversion techniques or where current generates a reference voltage

may use the compensation circuit. These applications are likely to use current mirroring techniques with reduced supply voltages.

While the invention has been particularly shown and described with reference to the preferred embodiments thereof, it will be understood by those skilled in the art
5 that various changes in form and detail may be made therein without departing from the spirit and scope of the invention.

WHAT IS CLAIMED IS:

1. A current compensation circuit for use with a current mirror circuit, the current mirror circuit having a current path defined by a first programmable current mirror stage driving a first fanout current mirror stage, the first programmable current mirror stage having at least one transistor with a channel length exhibiting a first
5 channel length modulation factor λ_1 , the first fanout current mirror stage coupled to a supply voltage source, the current compensation circuit comprising:
a supply voltage current mirror coupled to the supply voltage source, and having a current output coupled to the current path; and
a second programmable current mirror coupled in series with the
10 supply voltage current mirror and having at least one transistor with a channel length exhibiting a channel length modulation factor λ_2 , wherein the second channel length modulation factor λ_2 is larger than the first channel length modulation factor λ_1 , the first programmable current mirror and the second programmable current mirror cooperating to maintain a bias current through the first fanout current mirror stage
15 substantially independent of changes in the supply voltage.
2. A current compensation circuit according to claim 1 wherein each of the programmable current mirror stages comprises:
a parallel array of programmable transistors for defining a
predetermined range of current.
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3. A current compensation circuit according to claim 1 wherein the current compensation circuit is formed on a single integrated circuit device.
4. A current compensation circuit according to claim 3 wherein the current compensation circuit is formed in CMOS.
5. A current compensation circuit for use with a current mirror circuit, the current mirror circuit having a current path defined by a first programmable current mirror stage driving a first fanout current mirror stage, the first programmable current mirror stage having at least one transistor with a channel length exhibiting a first
5 channel length modulation factor λ_1 , the first fanout current mirror stage coupled to a supply voltage source, the current compensation circuit comprising:
means for detecting changes in the supply voltage from the supply voltage source, the means for detecting changes including means for generating a

compensation signal representative of voltage changes in the supply voltage source;
10 and
means for generating a compensation current for application to the
current mirror in response to the compensation signal.

6. A current compensation circuit according to claim 5 wherein the means
for detecting changes in the supply voltage comprises:

a supply voltage current mirror coupled to the supply voltage source,
and having a current output coupled to the current path; and

5 a second programmable current mirror coupled in series with the
supply voltage current mirror.

7. A current compensation circuit according to claim 6 wherein:

the second programmable current mirror includes at least one transistor
with a channel length exhibiting a channel length modulation factor λ_2 , such that the
second channel length modulation factor λ_2 is larger than the first channel length
5 modulation factor λ_1 ; and

the means for generating a compensation current comprises the first
and second programmable current mirrors cooperating to maintain a bias current
through the first fanout current mirror stage substantially independent of changes in
the supply voltage.

8. A method for compensating for supply-voltage-induced changes to a
desired current through a fanout current mirror, the method including the steps:

detecting changes in the supply voltage from a supply voltage source;
5 generating a compensation current to a current path node, the
compensation current representative of the voltage changes in the supply voltage
source, the compensation current based on the channel length modulation factor λ_2 of
a second programmable current source; and

sinking current from the current path node with a first programmable
10 current source having a first channel length modulation factor λ_1 less than that of λ_2 ,
wherein the level of current sunk corresponds to the difference between the
compensation current and the desired current through the fanout current mirror.

9. A timing generator for use in a semiconductor tester, the timing
generator including:

a delay line having a plurality of delay cells with respective phase-
shifted outputs and bias current inputs;

5 a selector having a plurality of inputs for receiving the phase shifted outputs, and an output;
 phase detection circuitry for detecting the phase shift between the selector output and a reference signal, and generating bias current; and
 fanout circuitry to distribute the bias current to the plurality of delay
10 cells, the fanout circuitry comprising a first programmable current mirror circuit and a first fanout current mirror circuit coupled to a supply voltage, the first programmable current mirror circuit and the fanout current mirror circuit cooperating to define a bias current path, and
 a current compensation circuit coupled to the fanout circuitry to
15 minimize changes to the bias current resulting from changes in the supply voltage, the current compensation circuit including at least two programmable current mirrors, each having respective channel length modulation factors λ_1 and λ_2 , one of the channel length modulation factors being larger than the other.

20 10. A timing generator according to claim 9 wherein the first programmable current mirror stage having at least one transistor with a channel length exhibiting a first channel length modulation factor λ_1 , the current compensation circuit comprising:

 a supply voltage current mirror coupled to the supply voltage source,
25 and having a current output coupled to the current path; and
 a second programmable current mirror coupled in series with the supply voltage current mirror and having at least one transistor with a channel length exhibiting a channel length modulation factor λ_2 , wherein the second channel length modulation factor λ_2 is larger than the first channel length modulation factor λ_1 , the
30 first programmable current mirror and the second programmable current mirror cooperating to maintain a bias current through the first fanout current mirror stage substantially independent of changes in the supply voltage.

 11. A timing generator for use in a semiconductor tester, the timing generator including:

 a delay line having a plurality of delay cells with respective phase-shifted outputs and bias current inputs;

5 a selector having a plurality of inputs for receiving the phase shifted outputs, and an output;

 phase detection circuitry for detecting the phase shift between the selector output and a reference signal, and generating bias current; and

 means for distributing the bias current to the plurality of delay cells.

- 10 12. A timing generator according to claim 11 wherein the means for
distributing comprises:
- fanout circuitry to distribute the bias current to the plurality of delay
cells, the fanout circuitry comprising
- a first programmable current mirror circuit, the first
- 15 programmable current mirror circuit having at least one transistor exhibiting a channel
length modulation factor λ_1 ;
- a fanout current mirror circuit coupled to a supply voltage, the
fanout current mirror and the first programmable current mirror circuits coupled at a
current node and cooperating to define a bias current path, and
- 20 a current compensation circuit comprising
- a supply voltage current mirror coupled to the supply
voltage source, and having a current output coupled to the current path; and
- a second programmable current mirror coupled in series
with the supply voltage current mirror and having at least one transistor with a channel
- 25 length exhibiting a channel length modulation factor λ_2 , wherein the second channel
length modulation factor λ_2 is larger than the first channel length modulation factor λ_1 ,
the first programmable current mirror and the second programmable current mirror
cooperating to maintain a bias current through the first fanout current mirror stage
substantially independent of changes in the supply voltage.

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