



US008324952B2

(12) **United States Patent Masters**

(10) **Patent No.:** US 8,324,952 B2  
(45) **Date of Patent:** Dec. 4, 2012

(54) **TIME INTERPOLATOR CIRCUIT**  
(75) Inventor: **Lewis W Masters**, Los Altos, CA (US)  
(73) Assignee: **Phase Matrix, Inc.**, San Jose, CA (US)  
(\* ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 28 days.

5,333,162	A	7/1994	Condrea	
5,359,404	A *	10/1994	Dunne	356/5.06
5,521,696	A *	5/1996	Dunne	356/5.07
5,631,553	A *	5/1997	Bose et al.	324/76.24
5,684,760	A	11/1997	Hunter	
5,703,678	A	12/1997	Dunne	
5,703,838	A	12/1997	Gorbics et al.	
6,137,749	A	10/2000	Sumner	
6,246,737	B1	6/2001	Kuglin	
6,324,125	B1	11/2001	Frankowsky et al.	
6,822,485	B2	11/2004	Kattan	
7,202,716	B1	4/2007	Chao et al.	
2009/0009455	A1 *	1/2009	Kimura	345/89

(21) Appl. No.: **13/101,038**

(22) Filed: **May 4, 2011**

(65) **Prior Publication Data**

US 2012/0281806 A1 Nov. 8, 2012

(51) **Int. Cl.**  
**H03H 11/16** (2006.01)

(52) **U.S. Cl.** ..... **327/231; 327/237**

(58) **Field of Classification Search** ..... None  
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,133,189	A	5/1964	Bagley et al.
3,204,180	A	8/1965	Bray et al.
3,983,481	A	9/1976	Nutt et al.
4,433,919	A	2/1984	Hoppe
4,439,046	A	3/1984	Hoppe
4,620,788	A	11/1986	Giger
4,719,608	A	1/1988	Genat et al.
4,764,694	A	8/1988	Winroth
4,772,843	A	9/1988	Asaka et al.
4,870,629	A	9/1989	Swerlein et al.
4,875,201	A	10/1989	Dalzell
5,132,558	A	7/1992	Rustici
5,191,336	A	3/1993	Stephenson
5,199,008	A	3/1993	Lockhart et al.
5,206,889	A	4/1993	Unkrich

OTHER PUBLICATIONS

Agilent Technologies, Application Note 200, Fundamentals of Electronic Counters.  
 Agilent Technologies, Application Note 200-1, Fundamentals of Microwave Frequency Counters.  
 Agilent Technologies, Application Note 200-3, Fundamentals of Time Interval Measurements.  
 Mota et al., "A High-Resolution Time Interpolator . . .", IEEE J. Solid State Circuits, v. 34, p. 1360 (1999).  
 Henzler et al., "A Local Passive Time Interpolation Concept . . .", IEEE J. Solid State Circuits, v. 43, p. 1666 (2008).  
 Jansson et al., "A CMOS Time-to-Digital Converter . . .", IEEE J. Solid State Circuits, v. 41, p. 1286 (2006).  
 Stevens et al., "A Time-to-Voltage Converter . . .", IEEE J. Solid State Circuits, v. 24, p. 1748 (1989).  
 Napolitano et al., "A Novel Sample-and-Hold-Based Time-to-Digital . . .", IEEE Trans. Inst. and Meas., v. 59, p. 1019 (2010).  
 Nissinen et al., "On-Chip Voltage Reference-Based Time-to-Digital . . .", IEEE Trans. Inst. and Meas., v. 58, p. 1938 (2009).

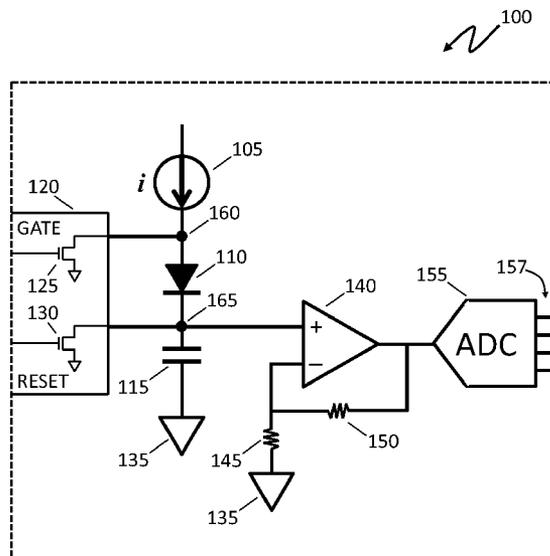
(Continued)

Primary Examiner — Cassandra Cox

(57) **ABSTRACT**

A time interpolator circuit increases the accuracy of digital counting circuits.

**11 Claims, 3 Drawing Sheets**



OTHER PUBLICATIONS

Xia et al., "Time-to-Voltage Converter . . .", IEEE Trans. Inst. and Meas., v. 52, p. 1738 (2003).

Tadokoro et al., "Simple Voltage-to-Time Converter . . .", IEEE Trans. Inst. and Meas., p. 120, May 1971.

Szplet et al., "Interpolating Time Counter . . .", IEEE Trans. Inst. and Meas., v. 49, p. 879 (2000).

Rakovich et al., "A Wide-Range Voltage-to-Time Converter", IEEE Trans. Inst. and Meas., v. IM-22, p. 162 (1973).

\* cited by examiner

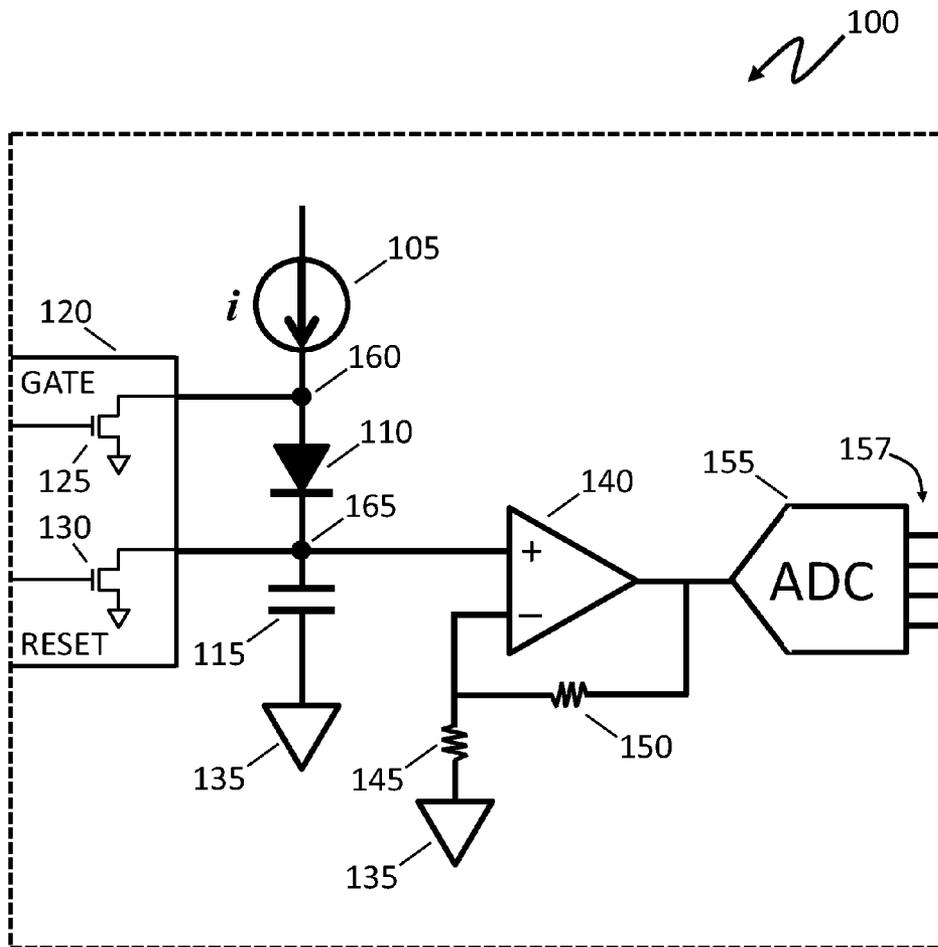


Fig. 1

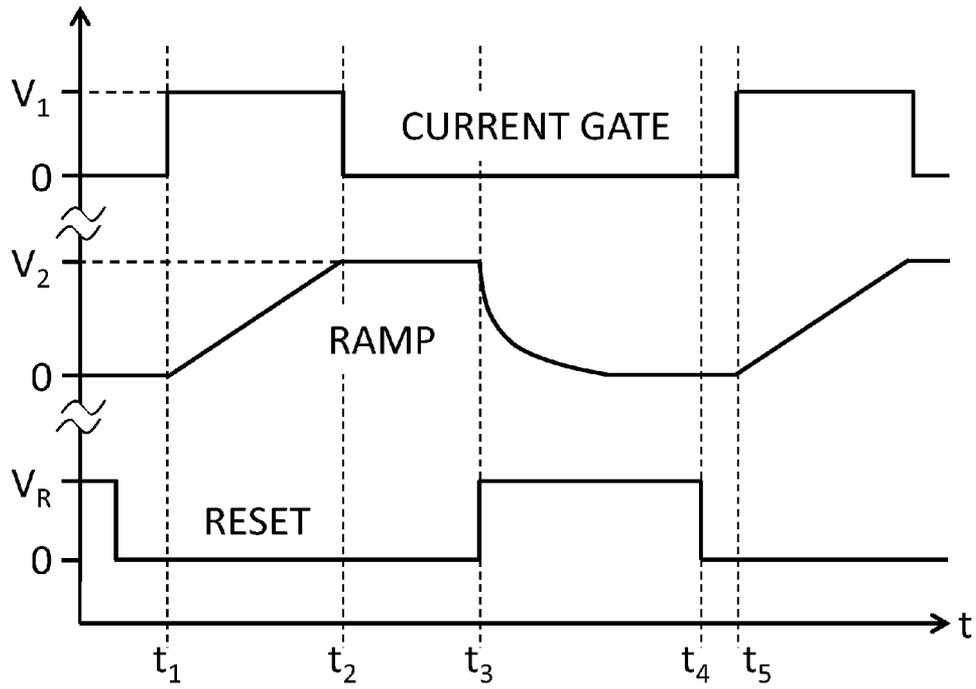


Fig. 2

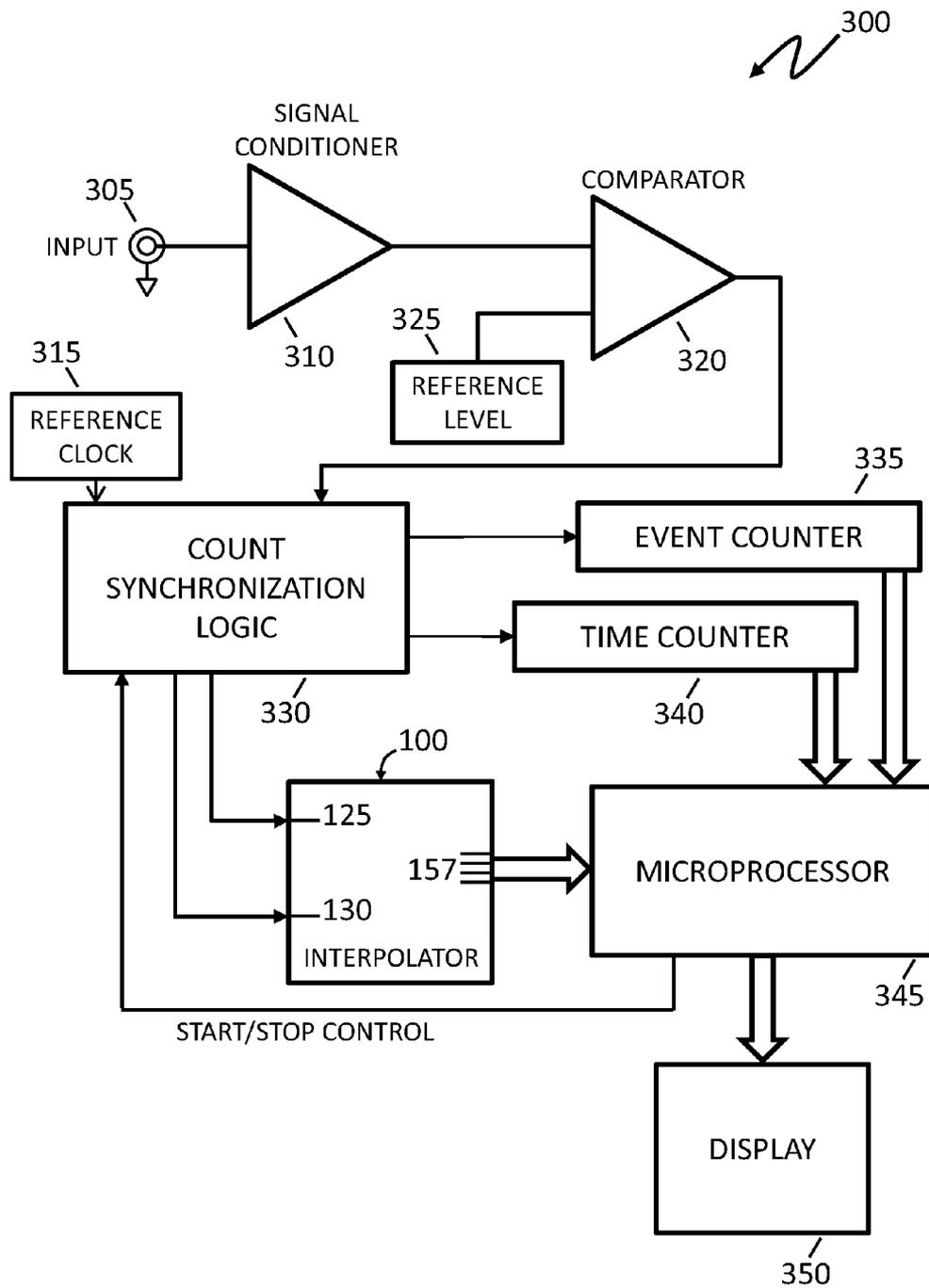


Fig. 3

## TIME INTERPOLATOR CIRCUIT

## TECHNICAL FIELD

The disclosure is related to time interpolator circuits.

## BACKGROUND

A time interpolator circuit increases the resolution and accuracy of time measurements beyond the limits of digital circuits. Time interpolators are commonly used in frequency counters, which are instruments that measure the number of cycles of a repetitive signal per second. In a typical reciprocal frequency counter, a digital circuit counts the number of electronic clock pulses that occur per cycle of a signal to be measured. The frequency is then proportional to the reciprocal of this number. In actual practice most frequency counters count the number of clock pulses that occur during a large number of signal cycles. Thus the counter may start counting clock pulses at one cycle of the signal and stop millions of signal cycles later.

As an example, suppose that a frequency counter has a clock that runs at 10 MHz and the signal to be measured has a frequency of roughly 1 GHz. The counter begins counting clock pulses at one signal cycle and stops 100 million signal cycles later. Suppose that 999,437 clock pulses are counted between the first and 100 millionth signal cycles. This result means that the frequency of the nominally 1 GHz signal is actually about 1.000563 GHz (100 million signal cycles divided by 0.0999437 seconds). It may not be exactly 1.000563 GHz, however, because the time between the first signal cycle and the first clock pulse, and the time between the last signal cycle and the last clock pulse, haven't been measured. A time interpolator is a circuit that accounts for these fractional times to improve measurement accuracy.

An early time interpolator circuit example is described in "Electronic interpolating counter for the time interval and frequency measurement" by Bagley and Brooksby (U.S. Pat. No. 3,133,189), and numerous variations and improvements have followed. Many interpolators rely on the charging characteristics of a capacitor connected to a current source. The voltage across such a capacitor is:

$$v = \frac{1}{C} \int Idt$$

where V is the voltage, C is the capacitance and I is the current flowing into the capacitor. If I is constant, as is the case with a good quality current source, then:

$$v = \left(\frac{I}{C}\right)t$$

Thus, the voltage across the capacitor is directly proportional to the time during which current is allowed to flow into it. Furthermore, this voltage can be measured quite accurately and precisely with an analog-to-digital converter.

Despite the long history of interpolator circuits, room for improvements exists. Thus what is needed is a simple, accurate interpolator circuit appropriate for modern frequency counters and similar devices.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram of a time interpolator circuit. FIG. 2 is a timing diagram for various signals in the circuit of FIG. 1.

FIG. 3 is a block diagram of a frequency counter incorporating the time interpolator circuit of FIG. 1.

## DETAILED DESCRIPTION

The time interpolator circuit described below provides good performance in frequency counters and other instruments. It is simple, inexpensive and easily interfaced to digital circuits.

FIG. 1 is a schematic diagram of a time interpolator circuit 100. In FIG. 1, current source 105 is connected to first circuit node 160, diode 110 is connected between first circuit node 160 and second circuit node 165, and capacitor 115 is connected between second circuit node 165 and ground 135. Logic circuit 120 contains switches 125 and 130 which are used to connect circuit nodes 160 and 165, respectively, to ground at various times. Switches 125 and 130 may be implemented as field effect transistors (FET) in a low-voltage logic chip, for example. Buffer amplifier 140, which may be implemented as an op-amp, is connected to circuit node 165. The amplifier presents high impedance to circuit node 165 and, along with feedback network resistors 145 and 150, scales the voltage at the node for input to analog-to-digital converter (ADC) 155. The digital output of the ADC is represented by lines 157.

Time is converted to voltage in the circuit of FIG. 1 through the charging of capacitor 115 by current source 105. Switch 125 is used to start and stop the charging, and switch 130 is used to discharge the capacitor after a measurement has been made. Diode 110 prevents the capacitor from discharging through switch 125 when that switch is on. The high-impedance input of buffer amplifier 140 allows the voltage across capacitor 115 (i.e. the voltage between circuit node 165 and ground) to be measured without discharging the capacitor. ADC 155 converts this voltage to digital form for further processing. Thus another name for the circuit of FIG. 1 is time to digital converter.

Buffer amplifier 140 and its feedback network resistors 145, 150 are not required if ADC 155 is able to directly measure the voltage across capacitor 115 without discharging it. In other words, the voltage measurement should not affect the capacitor voltage by more than the precision needed in a particular interpolation application. Whether or not a buffer amplifier is necessary depends on the input characteristics of the ADC.

The operation of the circuit of FIG. 1 may be understood in more detail by referring to FIG. 2 which is a timing diagram for various signals in the circuit. FIG. 2 illustrates the timing of a current gate signal, capacitor voltage ramp, and reset signal. The current gate signal shows when capacitor 115 is charging. When the current gate signal is zero current flows from current source 105 through switch 125 to ground. When the current gate signal is  $V_1$ , switch 125 is off (i.e. non-conducting) and current flows from current source 105 through diode 110 and into capacitor 115.

The capacitor voltage ramp shows the voltage across capacitor 115. The capacitor charges linearly with time when the current gate signal is  $V_1$  and stops charging when the current gate signal is zero. The voltage drop across diode 110 prevents capacitor 115 from charging when switch 125 is turned on. In other words the voltage drop across the diode is greater than the resistance of switch 125 in its conducting state multiplied by the current supplied by current source 105.

The reset signal shows when capacitor 115 is discharging. When the reset signal is  $V_R$  circuit node 165 is connected to ground through switch 130 and capacitor 115 discharges.

When the reset signal is zero, switch **130** is off (i.e. non-conducting) and the capacitor may charge depending on the state of switch **125**.

The circuit of FIG. **1** measures the time during which a current gate is open. In FIG. **2**, this means the time that the current gate signal is  $V_1$  (e.g. between times  $t_1$  and  $t_2$ ). Thus switch **125** controls the interpolation interval. Buffer amplifier **140** and ADC **155** measure the voltage across capacitor **115** after the end of the interpolation interval. Switch **130** resets the voltage to zero in preparation for the next measurement. Diode **110** prevents undesired charging and discharging of the capacitor.

At time  $t_1$  in FIG. **2** the current gate signal changes from zero to  $V_1$ . Switch **125** opens and therefore current from current source **105** flows through diode **110** and charges capacitor **115**. From time  $t_1$  to time  $t_2$ , the voltage across capacitor **115** (i.e. the voltage between circuit node **165** and ground) increases linearly with time as indicated by the capacitor voltage ramp. At time  $t_2$  the voltage across the capacitor has reached  $V_2$  which is proportional to the elapsed time between  $t_1$  and  $t_2$ :

$$V_2 = \left(\frac{I}{C}\right)(t_2 - t_1)$$

where  $I$  is the current supplied by current source **105** and  $C$  is the capacitance of capacitor **115**.

This voltage remains constant and is available to be measured by buffer amplifier **140** and ADC **155** from time  $t_2$  until time  $t_3$ . At time  $t_3$  the reset signal changes from zero to  $V_R$  and switch **130** turns on, connecting circuit node **165** to ground and discharging capacitor **115**. The voltage across the capacitor rapidly decays to zero. Sometime before the next interpolation interval begins the reset signal changes back to zero at time  $t_4$  and the circuit is returned to the state it was in just before time  $t_1$ . A new interpolation interval starts at time  $t_5$ .

The time interpolator circuit of FIG. **1** may be incorporated into a frequency counter, time interval counter or other device that relies on time measurement such as a LIDAR transceiver. As an example, FIG. **3** is a block diagram of a frequency counter **300** incorporating the time interpolator circuit of FIG. **1**. The frequency counter of FIG. **3** is conventional except for time interpolator circuit **100**.

In FIG. **3** signals introduced at input **305** travel through signal conditioner **310** and comparator **320** before being input to count synchronization logic **330**. Signal conditioner **310** may include signal protection, automatic gain control, AC/DC coupling and filters while comparator **320** compares an input signal to reference level **325**. Count synchronization logic **330** also receives signals from reference clock **315** and start/stop control from microprocessor **345**. The count synchronization logic sends output signals to event counter **335**, time counter **340** and interpolator **100**. Microprocessor **345** receives digital input from the two counters and the interpolator and sends digital output to an optional display **350**.

Event counter **335** counts input events, e.g. pulses or cycles from input **305**. Time counter counts clock events, e.g. pulses from an internal clock or reference clock **315**. The counters send their results as digital data to microprocessor **345**. Interpolator **100** is started and stopped by the count synchronization logic via switches **125** and **130** as described above. The interpolator also sends its digital results via output **157** to microprocessor **345** which carries out the necessary calculations to estimate the frequency of a signal at input **305**. Interpolator **100** may interpolate between clock pulses at the

beginning and end of a counting interval. The results of a frequency measurement may be displayed by display **350**.

As another example, interpolator circuit **100** of FIG. **1** may be substituted for a conventional interpolator in a time interval counter in much the same way that the circuit is substituted for a conventional interpolator in the frequency counter in the example above. The architecture of a typical time interval counter has many similarities to that of a frequency counter; however, in a time interval counter start and stop synchronization logic blocks start and stop a time counter that counts pulses from a reference clock. Start and stop interpolators are used to keep track of the fractional clock pulse intervals that occur between a start signal and the next clock pulse, and between a stop signal and the next clock pulse.

In one implementation the interpolator described above provides approximately ten picosecond repeatability and is ready for a new measurement in less than one microsecond. Low-voltage logic interfacing is convenient when switches **125** and **130** are implemented as FETs. Regardless of specific implementation the circuit provides a simple, precise and inexpensive time-to-voltage conversion capability.

The above description of the disclosed embodiments is provided to enable any person skilled in the art to make or use the disclosure. Various modifications to these embodiments will be readily apparent to those skilled in the art, and the principles defined herein may be applied to other embodiments without departing from the scope of the disclosure. Thus, the disclosure is not intended to be limited to the embodiments shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

What is claimed is:

1. A time interpolator circuit comprising:

- a current source connected to a first circuit node;
- a diode connected between the first circuit node and a second circuit node;
- a capacitor connected between the second circuit node and ground; and,
- a logic circuit including a first switch capable of connecting the first circuit node to ground and a second switch capable of connecting the second circuit node to ground.

2. The time interpolator circuit of claim **1** further comprising:

- an analog-to-digital converter connected to the second circuit node.

3. The time interpolator circuit of claim **1** further comprising:

- an analog-to-digital converter for measuring voltage between the second circuit node and ground.

4. The time interpolator circuit of claim **1** further comprising:

- a buffer amplifier having an input connected to the second circuit node; and,

- an analog-to-digital converter connected to an output of the buffer amplifier.

5. The time interpolator circuit of claim **4**, the buffer amplifier comprising an operational amplifier and a feedback resistor network.

6. The time interpolator circuit of claim **4**, the buffer amplifier input having impedance high enough to prevent discharging the capacitor through the amplifier.

7. The time interpolator circuit of claim **4**, the analog-to-digital converter measuring a voltage between the second circuit node and ground as scaled by the amplifier.

8. The time interpolator circuit of claim **1**, the first and second switches being field effect transistors.

5

9. The time interpolator circuit of claim 1, the diode preventing current flow from the second circuit node to the first circuit node.

10. A frequency counter comprising:  
count synchronization logic having signal, reference clock, 5  
and start/stop control inputs;  
an event counter and a time counter both connected to the  
count synchronization logic;  
a microprocessor that receives digital input from the  
counters and sends a start/stop control signal to the count 10  
synchronization logic; and,  
an interpolator according to claim 3, the interpolator's first  
and second switches connected to the count synchroni-

6

zation logic and digital output from the interpolator's analog-to-digital converter connected to the microprocessor.

11. A time interval counter comprising:  
start synchronization logic and stop synchronization logic;  
a time counter connected to the start synchronization logic  
and to the stop synchronization logic;  
a first interpolator according to claim 3, the first interpo-  
lator connected to the start synchronization logic; and,  
a second interpolator according to claim 3, the second  
interpolator connected to the stop synchronization logic.

\* \* \* \* \*