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Staszewski et al.

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(54) **FREQUENCY SYNTHESIZER WITH DIGITALLY-CONTROLLED OSCILLATOR**

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(\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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This patent is subject to a terminal disclaimer.

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(57) **ABSTRACT**

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**Related U.S. Application Data**

(63) Continuation of application No. 10/006,607, filed on Nov. 30, 2001.

(60) Provisional application No. 60/286,572, filed on Apr. 25, 2001, and provisional application No. 60/313,749, filed on Aug. 20, 2001.

(51) **Int. Cl.**<sup>7</sup> ..... **H03L 7/00**

(52) **U.S. Cl.** ..... **331/36 C; 331/177 V**

(58) **Field of Search** ..... **331/36 C, 100, 331/117 R, 117 FE, 177 V; 375/376; 327/156**

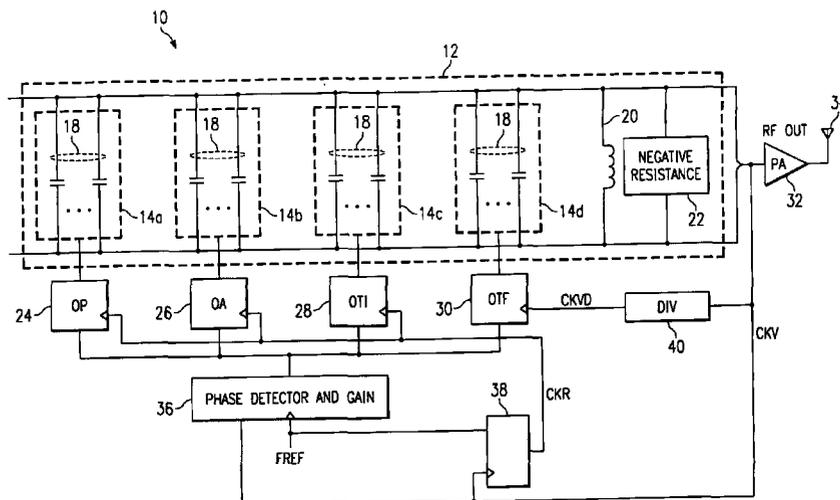
A transmitter (10) based on a frequency synthesizer includes an LC tank (12) of a digitally controlled oscillator (DCO) with various arrays of capacitors. The LC tank 12 is divided into two major groups that reflect two general operational modes: acquisition and tracking. The first group (process/voltage/temperature and acquisition) approximately sets the desired center frequency of oscillation initially, while the second group (integer and fractional tracking) precisely controls the oscillating frequency during the actual operation. For highly accurate outputs, dynamic element matching (DEM) is used in the integer tracking controller to reduce non-linearities caused by non-uniform capacitor values. Also, a preferred range of the integer tracking capacitor array may be used for modulation after the selected channel has been acquired. A digital sigma-delta modulator circuit (50) drives a capacitor array (14d) in response to the fractional bits of the error word. On mode switches, the accumulated error is recalculated to a phase restart value to prevent perturbations.

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**2 Claims, 10 Drawing Sheets**



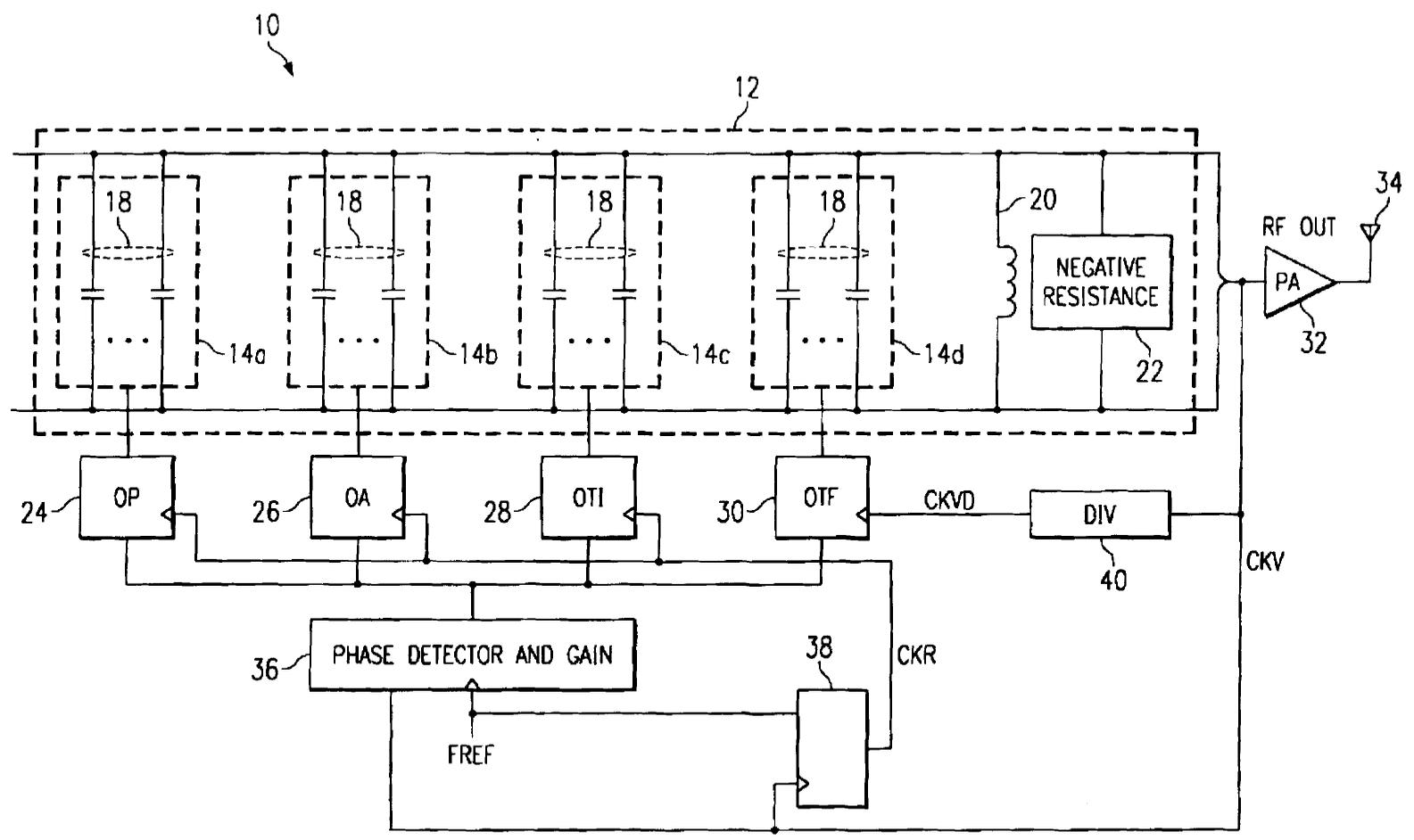


FIG. 1

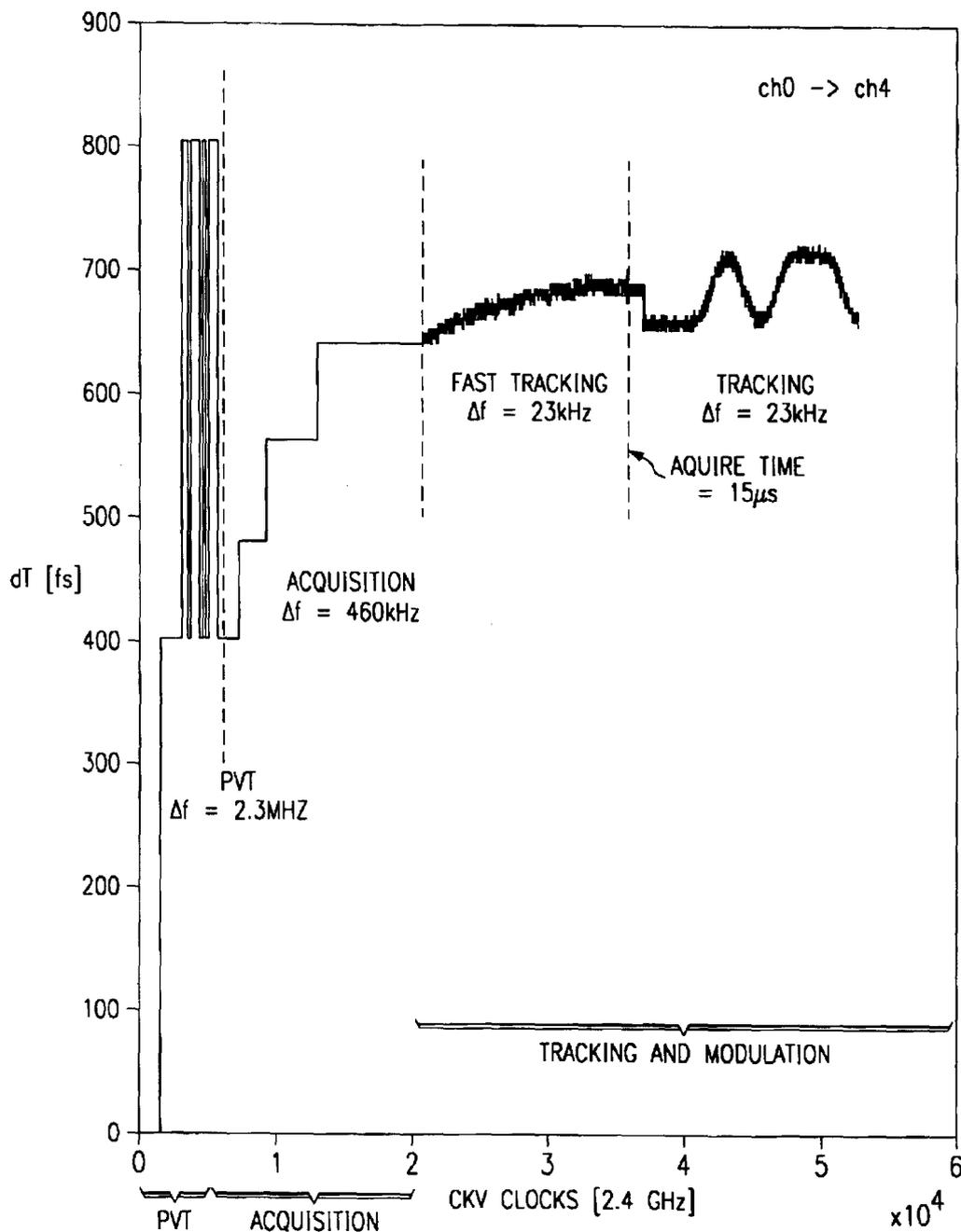


FIG. 2

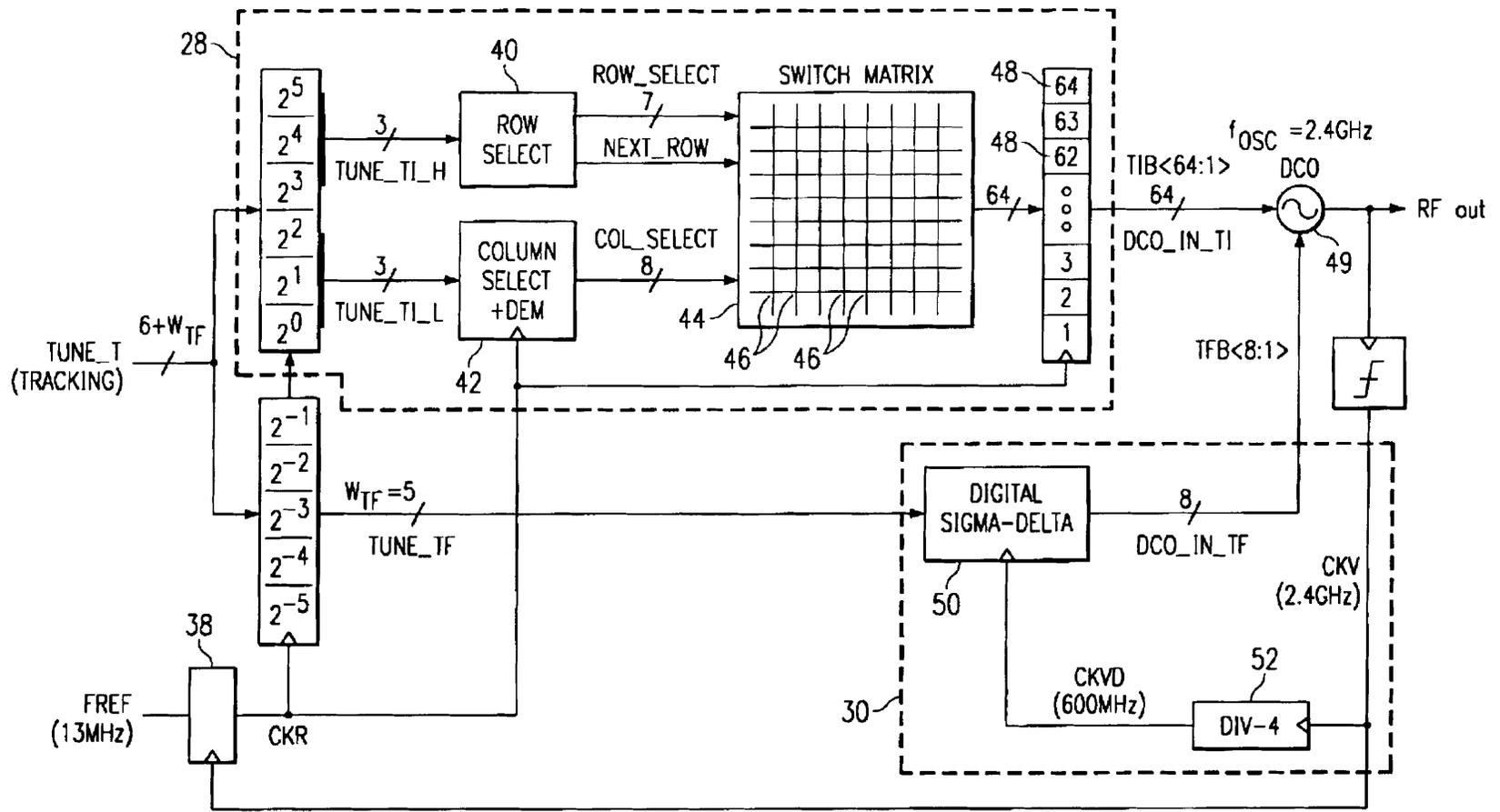
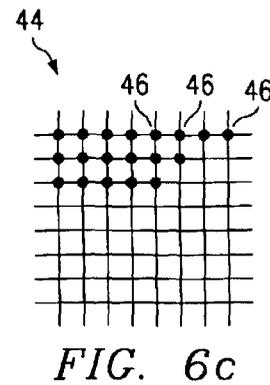
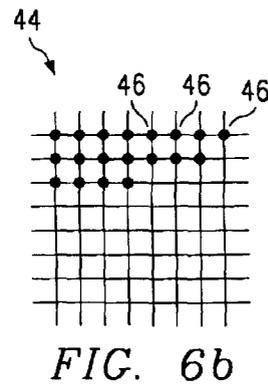
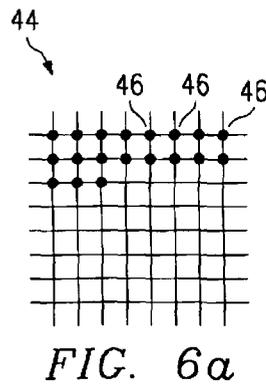
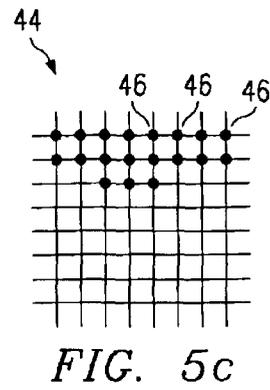
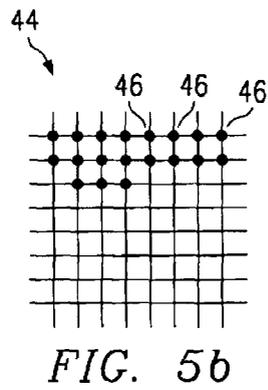
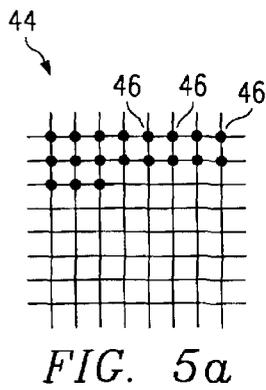
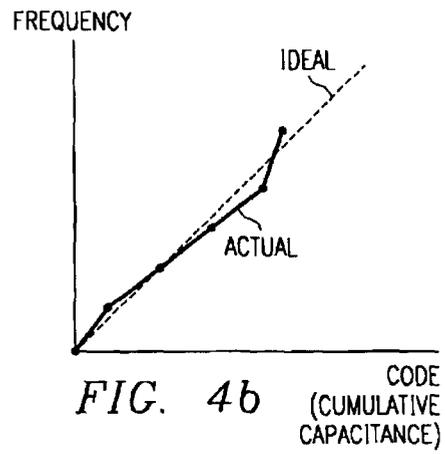
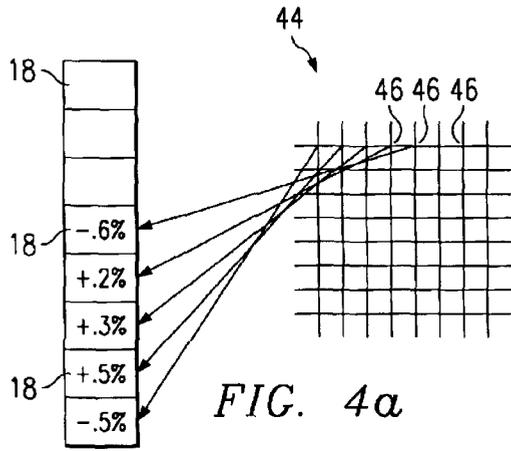


FIG. 3



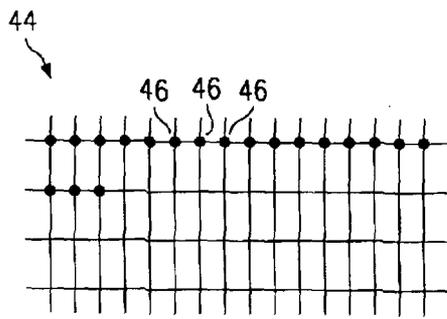


FIG. 7a

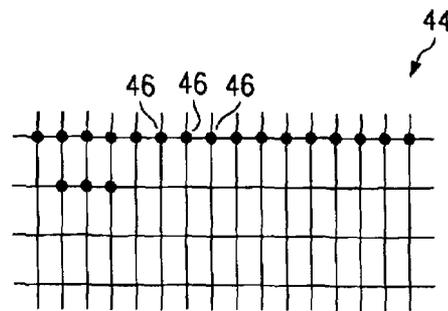
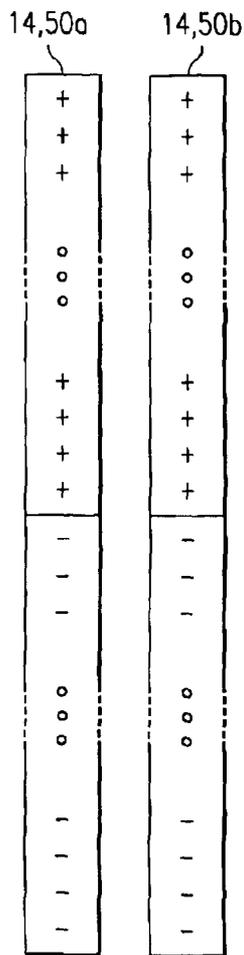
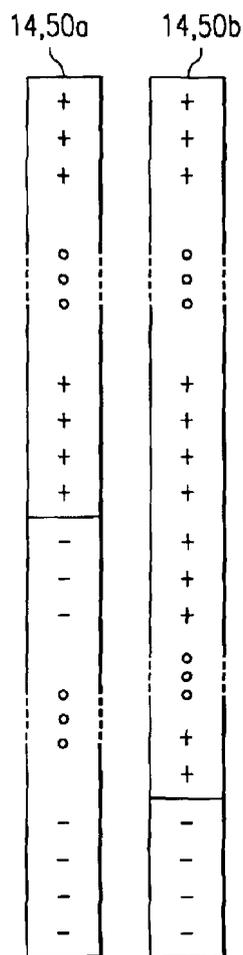


FIG. 7b



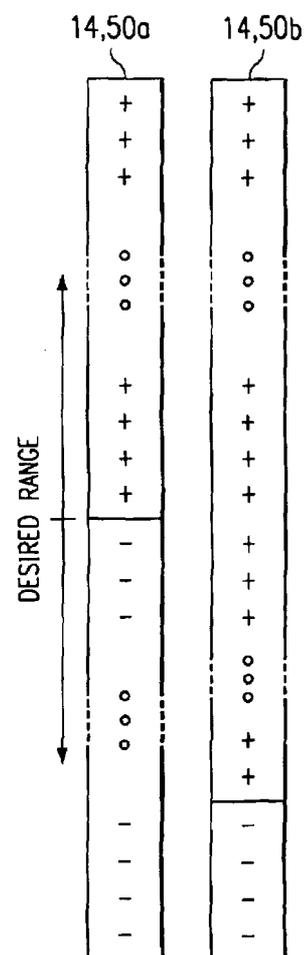
INITIAL STATE

FIG. 9a



CHANNEL TUNING

FIG. 9b



MODULATION AND DRIFT

FIG. 9c

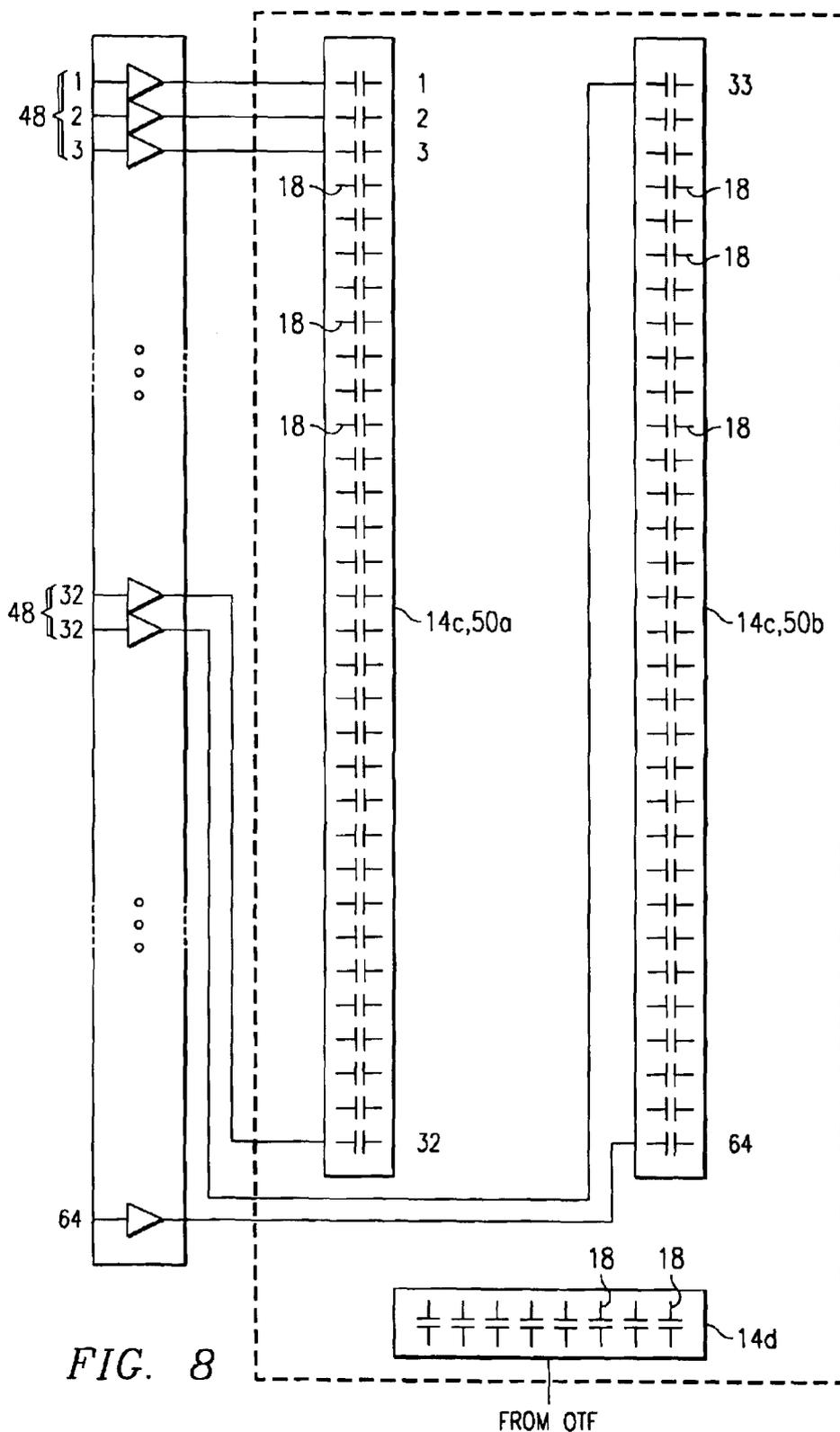


FIG. 8

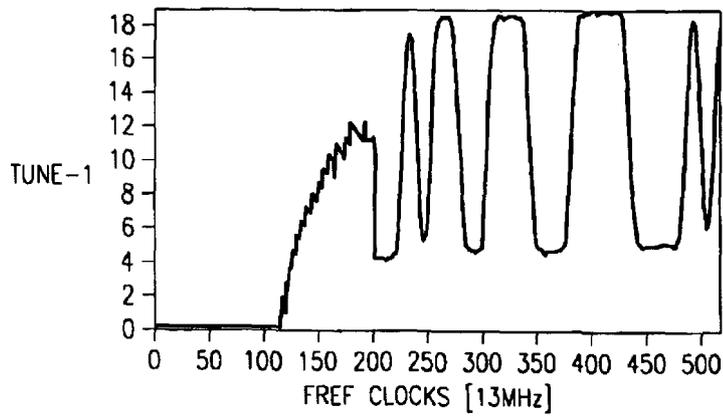
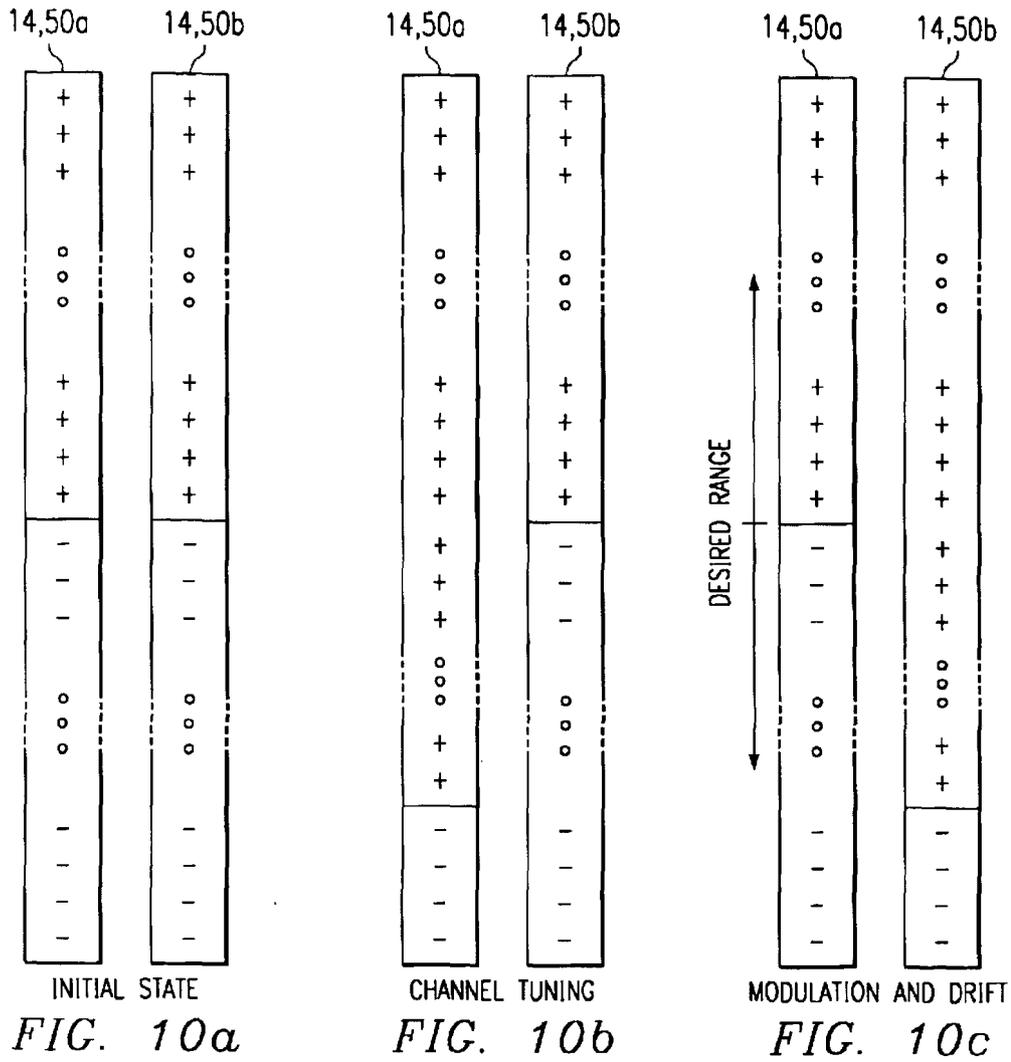


FIG. 11a

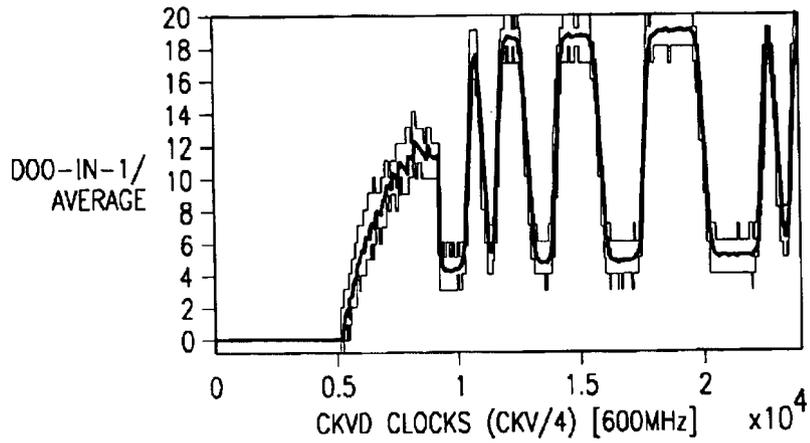


FIG. 11b

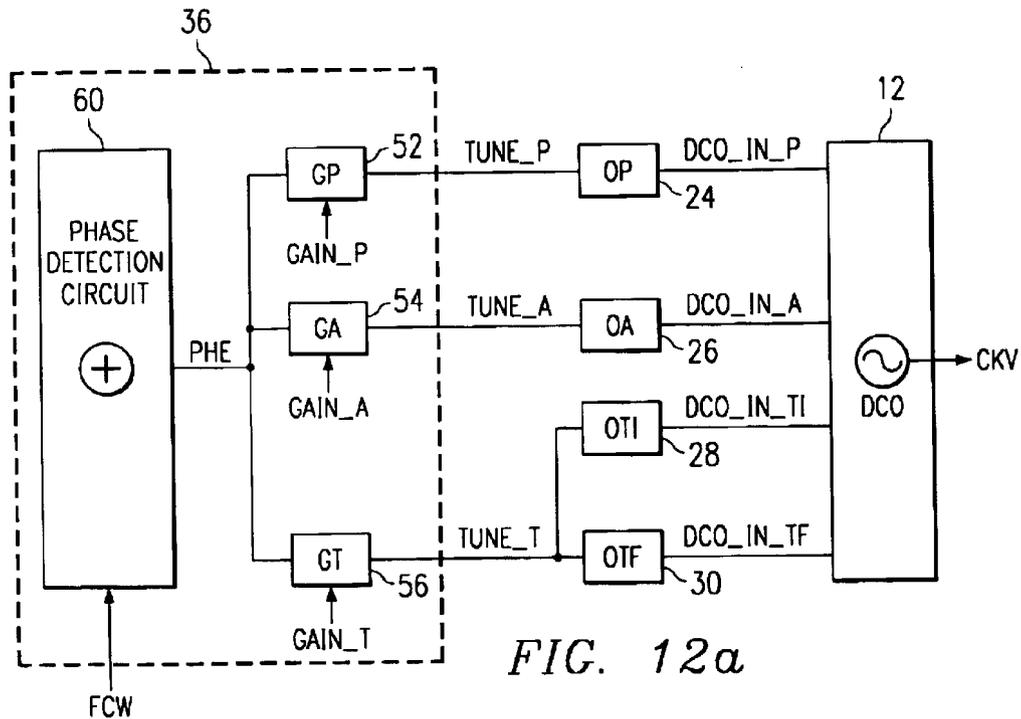


FIG. 12a

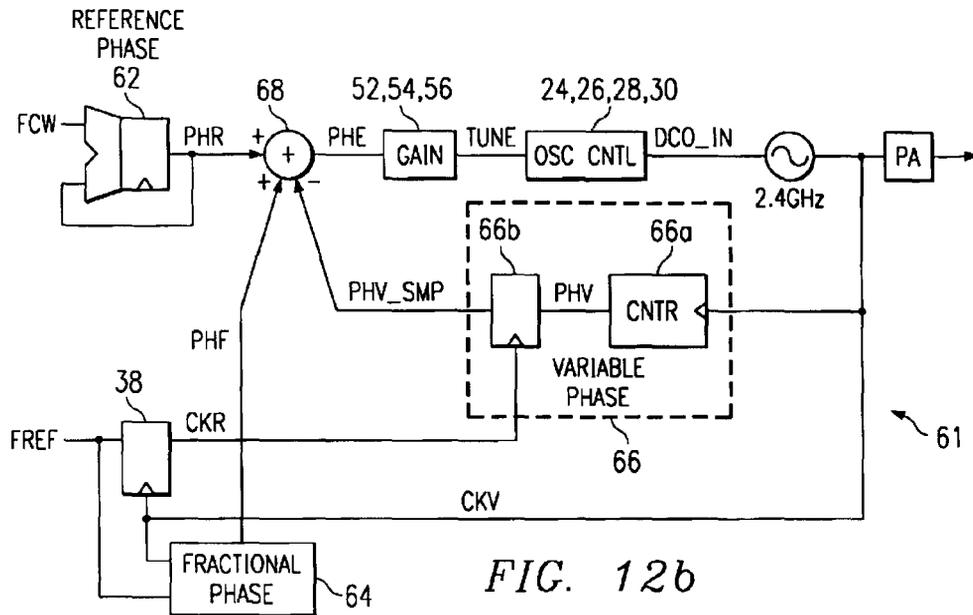


FIG. 12b

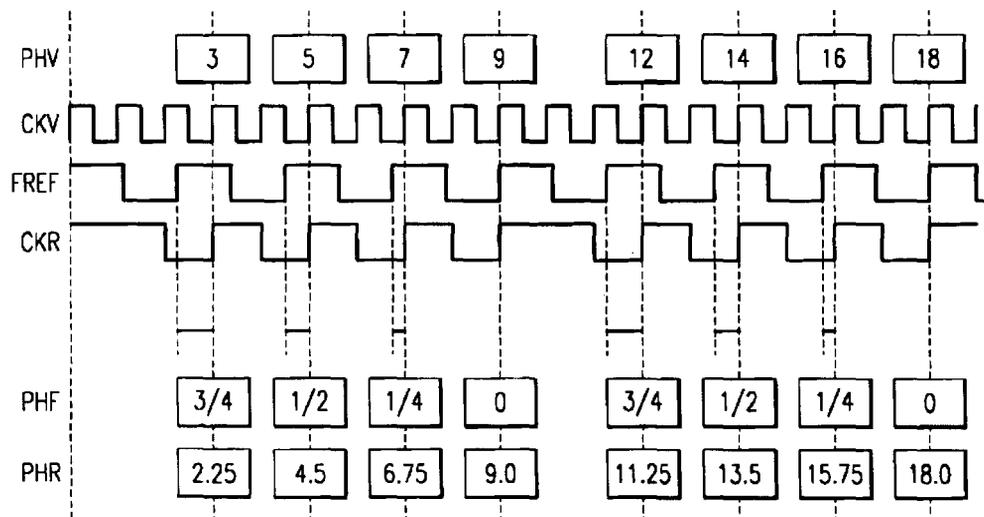
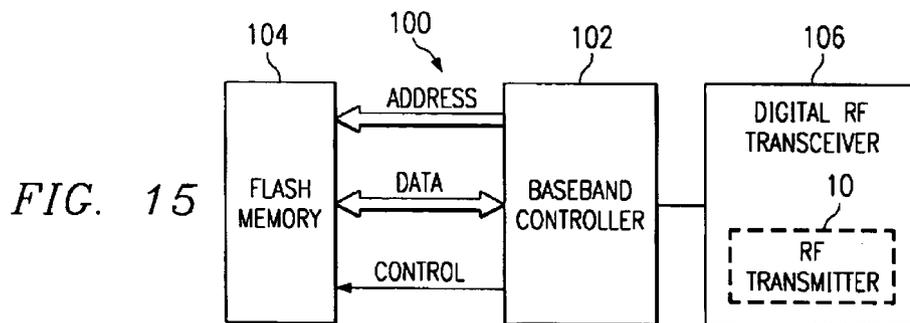
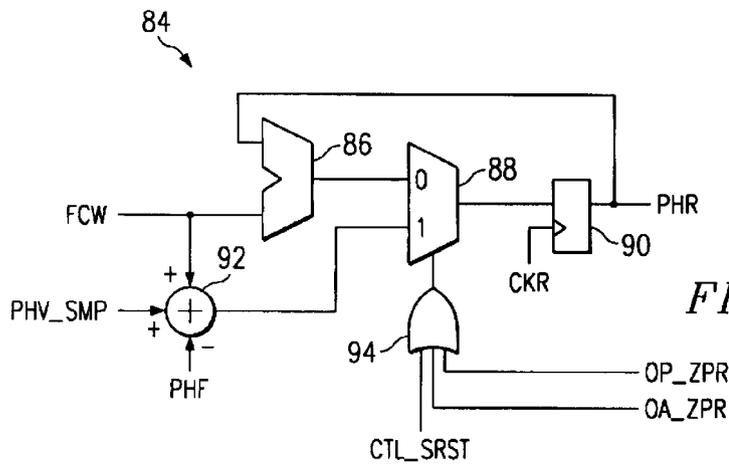
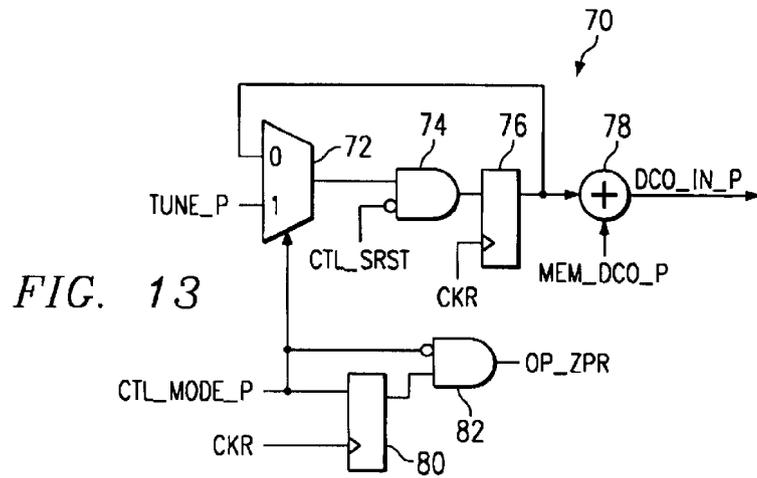


FIG. 12c



## FREQUENCY SYNTHESIZER WITH DIGITALLY-CONTROLLED OSCILLATOR

### CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of application Ser. No. 10/006,607 filed Nov. 30, 2001, which claims the benefit of the filing date of copending provisional applications U.S. Ser. No. 60/286,572, filed Apr. 25, 2001, entitled "Frequency Synthesizer Architecture of the Digital Radio Processor (v2.0)" to Staszewski et al and U.S. Ser. No. 60/313,749, filed Aug. 20, 2001, entitled "Power Saving Circuitry Using Predictive Logic" to Staszewski et al.

### STATEMENT OF FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

Not Applicable

### BACKGROUND OF THE INVENTION

#### 1. Technical Field

This invention relates in general to communications circuits and, more particularly, to frequency synthesizers and PLL loops with digitally controlled oscillators.

#### 2. Description of the Related Art

A great reduction of the transistor features in recently developed deep-submicron CMOS processes shifts the design paradigm towards more digitally-intensive techniques. In a monolithic implementation, the manufacturing cost of a design is measured not in terms of a number of devices used but rather in terms of the occupied silicon area, no matter what the actual circuit complexity.

Analog and RF (radio frequency) circuits used in communication circuits, however, are not easily implemented in a deep-submicron CMOS process. For example, in Texas Instruments' CMOS process (C035) of 0.08  $\mu\text{m}$  L-effective features a digital gate density of 150K equivalent (2-input NAND) gates per  $\text{mm}^2$ . An average-size inductor for an integrated LC oscillator occupies about 0.5  $\text{mm}^2$  of silicon area. A low-noise charge pump, or a low-distortion image-reject modulator, both good examples of classical RF transceiver components, occupy roughly about the same area, which could be traded for tens of thousands of digital gates.

Migrating to a digitally-intensive synthesizer architecture brings forth the following well-known advantages: (1) fast design turn-around cycle using automated CAD tools (VHDL or Verilog hardware-level description language, synthesis, auto-place and auto-route with timing-driven algorithms, parasitic backannotation and postlayout optimization), (2) much lower parameter variability than with analog circuits, (3) ease of testability, (4) lower silicon area and dissipated power that gets better with each CMOS technology advancement (also called a "process node") and (5) excellent chances of first-time silicon success. Commercial analog circuits usually require several design iterations to meet marketing requirements.

There is a wide array of opportunities that integration presents. The most straightforward way would be to merge various digital sections into a single silicon die, such as DRAM or Flash memory embedded into DSP or controller. More difficult would be integrating the analog baseband with the digital baseband. Care must be taken here to avoid coupling of digital noise into the high-precision analog section. In addition, the low amount of voltage headroom challenges one to find new circuit and architecture solutions. Integrating the analog baseband into RF transceiver section

presents a different set of challenges: The conventional Bi-CMOS RF process is tuned for high-speed operation with a number of available passive components and does not fundamentally stress high precision.

Sensible integration of diverse sections results in a number of advantages: (1) lower total silicon area. In a deep-submicron CMOS design, the silicon area is often bond-pad limited; consequently, it is beneficial to merge various functions on a single silicon die to maximize the core to bond-pad ratio, (2) lower component count and thus lower packaging cost, (3) power reduction—no need to drive large external inter-chip connections and (4) lower printed-circuit board (PCB) area, thus saving the precious "real estate."

Deep-submicron CMOS processes present new integration opportunities on one hand, but make it extremely difficult to implement traditional analog circuits, on the other. A digitally controlled oscillator (DCO) is very desirable, but it is important that the DCO be able to accurately track channels and modulate signals on a par with analog voltage controlled oscillators.

Therefore, a need has arisen for a method and apparatus for a high performance digitally controlled oscillator.

### BRIEF SUMMARY OF THE INVENTION

In a first aspect of the present invention, a frequency synthesizer comprises a digitally controlled oscillator, including a plurality of switched capacitors, and control circuitry for selectively enabling and disabling the capacitors responsive to an oscillator tuning word. The control circuitry includes select circuitry for enabling a number of capacitors responsive to the oscillator tuning word and circuitry for dynamically varying which capacitors are enabled for a given oscillator tuning word to reduce non-linearities caused by slight variances in capacitive values.

This aspect of the invention provides the advantage that non-linearities due to slight variations in capacitive values in the digitally controlled oscillator are smoothed out over time.

In a second aspect of the present invention, a frequency synthesizer comprises a digitally controlled oscillator, including a plurality of switched capacitors, and control circuitry for selectively enabling and disabling the capacitors. The control circuitry includes circuitry for tuning the digitally controlled oscillator to a selected frequency by enabling and disabling capacitors in a first set and circuitry for modulating the digitally controlled oscillator by enabling and disabling capacitors mainly in a second set.

This aspect of the invention provides the advantage that a preferred range of capacitors can be used for modulation and drift corrections.

In a third aspect of the present invention, a frequency synthesizer comprises a digitally controlled oscillator, including a first set of switched capacitors and a second set of switched capacitors, where the second set of switched capacitors are in a physically separate area from the first set of switched capacitors, and control circuitry for selectively enabling and disabling the capacitors responsive to an oscillator tuning word. The control circuitry comprises first tracking circuitry for enabling and disabling capacitors responsive to an first portion of the oscillator tuning word and a first clock and second tracking circuitry for enabling and disabling capacitors responsive to a second portion of the oscillator tuning word and a second clock, wherein the second clock is significantly faster than the first clock.

This aspect of the invention provides the advantage that corrections associated with a rapidly changing part of a

correction signal can be made with a physically separate set of capacitors, without contaminating the capacitors used for corrections responsive to a slower changing portion of the error signal.

### BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

For a more complete understanding of the present invention, and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

FIG. 1 illustrates a block diagram of RF transmitter circuit that is based on a frequency synthesizer with a direct frequency/phase modulation capability;

FIG. 2 illustrates operation of the various modes for controlling oscillation of the RF transmitter circuit;

FIG. 3 illustrates a block diagram of a tracking oscillator controller;

FIGS. 4a and 4b illustrate variation in capacitive values in the tracking capacitor array and non-linearities caused in the output caused thereby;

FIGS. 5a, 5b and 5c illustrate a first method of operation for the column select and DEM circuitry of the tracking oscillator controller;

FIGS. 6a, 6b and 6c illustrate a second method of operation for the column select and DEM circuitry of the tracking oscillator controller;

FIGS. 7a and 7b illustrate a different configuration for the switch matrix in conjunction with column select and DEM circuitry of the tracking oscillator controller;

FIG. 8 illustrates a layout diagram for the capacitors of the tracking capacitor arrays;

FIGS. 9a, 9b and 9c illustrate a first method of improving the quality of the output by using a desired range of capacitors in the tracking array;

FIGS. 10a, 10b and 10c illustrate a second method of improving the quality of the output by using a desired range of capacitors in the tracking array;

FIGS. 11a and 11b illustrate the use of sigma-delta modulation of the fractional tracking bits;

FIG. 12a illustrates a block diagram of the frequency synthesizer showing separate phase detector and gain circuits;

FIG. 12b illustrates a block diagram of a phase detection circuit in a generalized block diagram of a frequency synthesizer;

FIG. 12c illustrates a timing diagram showing signals from the frequency synthesizer of FIG. 12b.

FIG. 13 illustrates a block diagram of a PVT oscillator interface and phase restart generation circuit;

FIG. 14 illustrates a block diagram of a phase error restart correction circuit; and

FIG. 15 illustrates a block diagram of a mobile communication device using the RF transmitter of FIG. 1.

### DETAILED DESCRIPTION OF THE INVENTION

The present invention is best understood in relation to FIGS. 1–15 of the drawings, like numerals being used for like elements of the various drawings.

FIG. 1 illustrates a block diagram of RF transmitter circuit 10 that is based on a frequency synthesizer capable of directly modulating phase/frequency of oscillation. The RF

transmitter circuit 10 includes an LC tank 12 having multiple arrays 14a–d of switched capacitors 18 that are implemented as varactors in the preferred embodiment, an inductor 20 and a negative resistance 22 whose purpose is to perpetuate the oscillation. Switched capacitor arrays 14a–d are individually controlled by respective oscillator control circuits. A PVT (Process/Voltage/Temperature) oscillator controller (OP) 24 controls array 14a, acquisition oscillator controller (OA) 26 controls array 14b, integer tracking oscillator controller (OTI) 28 controls array 14c and fractional tracking oscillator controller (OTF) 30 controls array 14d. Each oscillator controller 24–30 can control the oscillation of the transmitter circuit by individually enabling and disabling individual capacitors 18 in its respective array 14a–d. Each capacitor 18 may be switched between high capacitive states and low capacitive states. Whether a capacitor is enabled or disabled depends upon its relative capacitive state. For illustration, it is assumed that a capacitor is “disabled” if it is placed in a low capacitive state and “enabled” if it is placed in a high capacitive state; in other embodiments, a capacitor could be enabled if it is placed in a low capacitive state and disabled if it is placed in a high capacitive state.

The output of the LC tank oscillator 12 is a differential clock signal CKV, which is received by the power amplifier 32. The output of power amplifier 32 is the RF output to the antenna 34. CKV is fed back to phase detector and gain circuit 36. Phase detector and gain circuit 36 also receives a reference frequency, FREF, typically the output of a crystal oscillator, and outputs an error signal to the oscillator controllers 24, 26, 28 and 30. FREF is also received by a flip-flop 38, which is clocked by CKV to produce a retimed reference clock CKR. CKR is used to clock oscillator controllers 24, 26 and 28. A divided CKV clock, CKVD, is produced by divider circuit 40, which could be a divide-by-4 circuit. CKVD clocks the fractional tracking oscillator controller.

The architecture shown in FIG. 1 could be used for a variety of wireless communication applications; for purposes of illustration, specifics will be discussed in view of a Bluetooth implementation. In this implementation, the PVT array 14a uses eight switched capacitors in a binary-weighted arrangement. The PVT array 14a has an incremental change in frequency of  $\Delta f=2.316$  MHz. Similarly, the acquisition array 14b uses eight switched capacitors in a binary-weighted arrangement. The acquisition array 14b has an incremental change in frequency of  $\Delta f=461$  kHz and a range of 118 MHz. There are two tracking arrays, an integer tracking array 14c and a fractional tracking array 14d. The integer tracking array includes sixty-four unit-weighted capacitors each capable of a  $\Delta f=23$  kHz, with a range of 1.472 MHz. The fractional tracking array includes eight unit-weighted capacitors,  $\Delta f=23$  kHz; these capacitors are matched to the capacitors of the integer tracking array 14c.

From the operational perspective, the LC tank 12 is divided into two major groups that reflect two general operational modes: acquisition and tracking. The first group approximately sets the desired center frequency of oscillation initially, while the second group precisely controls the oscillating frequency during the actual operation. During acquisition, the frequency range is quite high but the required resolution is relatively low, therefore a binary-weighted structure may be the best arrangement for the capacitor arrays 14a and 14b, although other structures could be used.

The acquisition group of switched capacitors is further divided into two subgroups: environmental and channel

select. The environmental subgroup corrects the center oscillating frequency of the operational band due to process-voltage-temperature (PVT) variations and could be performed at manufacturing, on power-up or on “as needed” basis. The channel select capacitor array **14b** controls the frequency acquisition process for the desired transmission channel. Both groups are best implemented using individual binary-weighted capacitance structures, but their ranges could be overlapping. There is no need to preserve the binary-weight continuity between the environmental and channel select structures due to the different origin of their respective control inputs. The PVT correction is infrequent and might be done directly through register interface, whereas the channel select DCO control input is performed dynamically and is an integral part of the synthesizer PLL (phase locked loop).

The tracking-mode operation presents, on the other hand, a different set of requirements. The frequency range is relatively low but the required resolution is quite high. The binary-weighted capacitance arrangement of the tracking mode is a poor choice here, because of binary switching noise, poor device matching of different size devices, and so on. A better structure is an array of unit devices of fine but identical dimensions. Further refinement of the frequency resolution is obtained by performing a high-speed dither of one or few of the tracking bits. It is implemented with a first, second or third order of a  $\Sigma\Delta$  modulator of the fractional part of the tracking phase error.

FIG. 2 illustrates operation of the various modes. At a cold power up, the transmitter core **10** enables the PVT oscillator controller **24**. This controller makes very coarse (2.315 MHz) adjustments to the frequency. Next, the output of the PVT oscillator controller is put on hold and the acquisition oscillator controller **26** is enabled. The acquisition oscillator controller **26** quickly brings the frequency near the selected channel in 460 kHz steps.

After acquisition of the selected channel is complete, the output of the acquisition oscillator controller **26** is put on hold and the tracking oscillator controllers **28** and **30** are enabled. The finest selection of the requested channel can only be accomplished using the tracking bank varactors with all the resolution enhancement techniques possible for this capacitor bank. The dynamic range of this mode has to cover the frequency resolution grid of the preceding acquisition mode. In this mode, the frequency steps are very fine but the loop bandwidth could be as fast as in the acquisition mode. The tracking oscillator controllers **28** and **30** first fine tune the channel select and then perform the modulation of the output signal RF OUT.

FIG. 3 illustrates a block diagram of the tracking oscillator controllers **28** and **30**. In the illustrated embodiment, the TUNE\_T, the tuning word output from the phase detectors and gain circuit **36**, has six integer bits and five fractional bits. The integer bits are processed by the integer tracking oscillator controller **28** and the fractional bits are processed by the fractional tracking oscillator controller **30**. The integer tracking oscillator controller **28** includes a row select circuit **40** and a column select and DEM (dynamic element matching) circuit **42**. The outputs of the row select circuit **40** and a column select and DEM circuit **42** are received by a switch matrix **44**. The switch matrix **44** provides sixty-four discrete switches **46** (corresponding to the sixty-four switched capacitors in the integer tracking array **14c**) that may be enabled or disabled by the row select circuit **42** and column select and DEM circuit **42** responsive to TUNE\_T. The switch matrix is coupled to a bank of sixty-four resampling drivers **48**, each individual resampling

driver **48** having a respective switch **46** and a respective capacitor **18** in switched capacitor array **14c**. The resampling drivers **48** selectively enable or disable capacitors in the integer tracking array **14c** in response to the associated switches **46**. Using resampling drivers **48** clocked at CKR eliminates timing errors due to path differences. The various capacitor arrays **14a-d** of the LC tank **12** are part of the DCO **49**.

The row select circuit **40**, column select circuit **42** and resampling drivers **48** are clocked by CKR. It should be noted that while the switch matrix is shown in a row/column configuration, an actual implementation may not be a precise grid. Hence, a “row” could be any predefined group of switches in the matrix.

The fractional tracking oscillator controller **30** includes a digital sigma-delta modulator circuit **50** that drives the individual capacitors **18** in the fractional tracking array **14d** in response to the fractional bits of the TUNE\_T word. The digital sigma-delta circuit is clocked by CKVD, which is assumed, in the illustrated embodiment, to be one-fourth of the 2.4 GHz CKV clock. Accordingly, the fractional tracking oscillator controller **30** is capable of switching capacitors in array **14d** at a frequency of 600 MHz, while the integer tracking oscillator controller **28** switches capacitor at a frequency of 13 MHz.

FIGS. 4a-b illustrate a problem that is addressed by the DEM circuitry in the column select and DEM circuit **42**. As shown in FIG. 4a, each switch **46** in the switch matrix **44** controls a capacitor **18** in array **14c**. Ideally, each of the capacitors **18** in array **14c** has the exact same capacitive value. Using real-world process fabrication, however, the capacitive value of each capacitor **18** will vary slightly from the ideal. As capacitors are enabled or disabled by the integer tracking oscillator controller **28**, non-linearities will be evident in the output due to the variations in capacitive values, as shown in FIG. 4b.

The operation of the column select and DEM circuitry **42** is shown in FIGS. 5a-c. In this example, the capacitors **18** associated with an unfilled row of the switch matrix **44** are rotated on each CKR clock cycle (or faster). In FIG. 5a, the first three columns of row three are enabled. In FIG. 5b, on the next CKR clock cycle, columns two through four, rather than columns one through three, are enabled. On the next clock cycle, columns three through five are enabled.

Accordingly, on each CKR clock cycle, the set of capacitors used in the array **14c** changes slightly. Over time, the non-linearities shown in FIG. 4b average out, thereby producing a much more accurate output.

In FIGS. 5a-c, the enabled switches for a single row are rotated. This can be accomplished, for example, by incrementing (or decrementing) the starting column of the enabled switches on each clock cycle. This method could be varied slightly by including two (or more) rows in the rotation, as shown in FIGS. 6a-c, where the last unfilled row and previous row are rotated.

Another variation is to vary the configuration of the switching matrix **44**, to lengthen (or shorten) the number of columns per row. In FIGS. 7a-b, the switch matrix is configured as a 4x16 matrix, rather than the 8x8 matrix shown in FIGS. 5a-c. As before, the enabled switches **46** are rotated on each clock cycle. The larger rows may provide a better output because a greater number of capacitors will be included in the rotation.

FIG. 8 illustrates a layout diagram for the capacitors **18** of arrays **14c** and **14d**. As can be seen in FIG. 8, capacitor array **14c** is arranged in two separate columns **50a** and **50b**,

although the capacitors could be arranged in any number of columns depending upon various layout issues. The fractional tracking array **14d** is separate from capacitor array **14c**.

As is evident in FIG. 8, the capacitors in column **50a** are closer to the resampling drivers **48** than are the capacitors in column **50b** and can be accessed by a relatively straight path. During modulation, if the signals that turn the capacitors in column **50b** on and off take longer than the signals to reach the other capacitors in column **50a**, non-linearities and glitches will be introduced into the output signal.

FIGS. **9a-c** illustrate a first method of improving the quality of the output. In the initial state, shown in FIG. **9a**, half of the capacitors in each column **50a** and **50b** are turned on (as designated by a "+") and half are turned off (as designated by a "-"). During tracking, the capacitors in the less desirable column **50b** are enabled or disabled in order to fine tune the oscillator to the selected channel, to the extent possible. If additional capacitors need to be enabled or disabled, capacitors in column **50a** may be used, preferably those capacitors at the edges of the column. After channel tuning, the capacitors in column **50a** are used for modulation and drift. In this way, the most desirable capacitors are used for generating the signal once data is being transmitted.

It should be noted that while the preferred center point was shown as the middle of column **50a**, the preferred center point could be set at any location in either column. Even for a single column of capacitors, a desirable range of capacitors could be defined and the preferred center point set to the middle of that range. Capacitors outside of the desired range could be used for channel tuning; once channel tuning was completed, the desired range could be used for modulation and drift. The center of the desired range need not be in the center of a column.

FIGS. **10a-c** illustrate an alternative embodiment for using the most desirable range for modulation. Starting from the same initial state in FIG. **10a**, channel tuning occurs in FIG. **10b** without regard for a desired range of capacitors. Once channel tuning is complete, the switch matrix **44** is rearranged, such that the desired range is restored and the capacitors in the less desirable locations are selected for the (already accomplished) channel tracking. Once modulation begins, the capacitors in the desired range are used.

Referring again to FIG. **3**, a digital sigma-delta modulator **50** is used to perform a high-speed dither of the fractional tracking bits. The sigma-delta modulator may be implemented using a first, second, or third order sigma-delta modulator. This method trades the sampling rate for the resolution. For example, if the frequency resolution of the 2.4 GHz DCO is  $\Delta f^{(T)}=23$  kHz with a 13 MHz update rate, then the effective time-averaged frequency resolution after a 600 MHz  $\Sigma\Delta$  dither with five sub-LSB bits is  $\Delta f^{(T-\Sigma\Delta)}=23$  kHz/ $2^5=718$  Hz.

The fractional path of the DCO tracking bits, which undergoes high-speed dithering, is entirely separated from the lower-speed integer part. A dedicated DCO input avoids "contaminating" the rest of the tracking bits with frequent transitions. The actual merging of both parts is performed inside the oscillator through time-averaged capacitance summation. Additionally, the fractional tracking bank **14d** can be implemented in a small area, where the fabrication may be optimized for the performance of the high-speed tracking. It should be noted that CKVD is synchronous to CKR, which reduces spurs in the RF output.

FIG. **11a** illustrates a fixed point DCO tuning word operating at FREF (13 MHz). FIG. **11b** illustrates DCO

input word operating at CKVD, with the black line in the middle being the running average.

FIG. **12a** illustrates a more detailed block diagram of the phase operation portion of the RF transmitter **10**. The phase detector and gain circuit **36** includes individual PVT, acquisition and tracking gain circuits **52**, **54** and **56** and a phase detection circuit **60**. The phase error (PHE) output of the phase detector is received by the gain circuits **52-56** (each gain circuit uses an individual set of bits of PHE). The gain circuits **52-56** multiply the respective portions of PHE by an associated factor, GAIN\_P; GAIN\_A and GAIN\_T. The outputs of the gain circuits, TUNE\_P, TUNE\_A and TUNE\_T are the oscillator tuning words that control the oscillator control circuits **24**, **26** **28** and **30**. As described in greater detail above, the oscillator control circuits sequentially control the DCO **12** through start-up, acquisition and tracking phases.

FIG. **12b** illustrates the phase detection circuit **60** in a frequency synthesizer circuit **61**. The phase detection circuit **60** includes a reference phase accumulator **62** that calculates a reference phase signal (PHR), a fractional error correction circuit **64** that calculates a fractional error correction (PHF), and a variable phase accumulator **66** that calculates a variable phase correction (PHV\_SMP, which is integer only). The phase error (PHE) is calculated by phase detector **68** as  $PHE=PHR+PHF-PHV\_SMP$  (with proper bit alignment to line up integer and fractional portions).

FCW (frequency control word) is the ratio of the desired frequency of CKV divided by the frequency of FREF. FREF is typically the output of a crystal oscillator. The reference phase signal is an accumulation of FCW at the active edge of CKR, which is the retimed FREF clock. The FCW input to the reference accumulator **62** is used to establish the operating reference phase of the desired channel plus the modulation data.

The variable phase accumulator **66** comprises a counter **66a**, which increments on each active edge of CKV and a latch **66b** that latches the output of the counter at CKR.

The fractional phase circuit **64** determines a difference between an active edge of FREF and the next active edge of CKV, normalized to as a fraction of a CKV clock cycle.

Operation of the circuit is best understood in relation to the timing diagram of FIG. **12c**, where an example of  $FCW=2.25$  is used. In an actual circuit, however, FCW would typically be much higher. For purposes of illustration, FCW is a constant (i.e., no modulation) and there is no drift. As described above, the variable phase circuit **66** counts the CKV clocks and latches the count on the active (rising) edge of CKR. The PHV from the variable phase circuit **66** counts are provided above the CKV signal. Also at each active edge of CKR, the reference phase circuit **62** accumulates another FCW.

At any active edge of CKR, the preceding active edge of FREF may have occurred at a point less than one CKV clock cycle earlier (since CKR is retimed to CKV). This is shown by the dashed lines in FIG. **12c**. PHF measures this fractional part of a CKV cycle. As can be seen in FIG. **12c**, for the steady state situation, without drift or modulation, the addition of PHF and PHR will equal PHV and PHE will be zero.

During normal operation, however, the PHE will often be non-zero. As described above, the PVT oscillator controller **24**, acquisition oscillator controller **26** and tracking controllers **28** and **30** operate one after another. The acquisition controller **26** starts after the oscillation controller **24** stops and the tracking controllers **28** and **30** operate after the

acquisition controller 26 stops. At the point of a mode switch (from startup to acquisition or from acquisition to tracking), the value of the PHE change can be quite large. If the existing PHE is used immediately after a switch, a large perturbation can occur.

The circuits shown in FIGS. 13 and 14 restart the phase error at the correct value during a mode change. The circuit of FIG. 13 is a PVT-oscillator interface and phase restart generation circuit 70 in the PVT oscillator controller 24 that preserves the correct capacitor configuration in array 14a and sends a mode change signal when the PVT oscillator controller 24 has completed its function. In FIG. 13, CTL\_MODE\_P is high during the operation of the PVT oscillator controller 24. When CTL\_MODE\_P is high, TUNE\_P is passed through multiplexer 72, AND gate 74, and flip-flop 76. TUNE\_P is added to MEM\_DCO\_P (generally, the last frequency estimate from the controller's lookup table) by adder 78. The output, DCO\_IN\_P, is used to enable/disable capacitors 18 in array 14a of the DCO. The synchronous reset CTL\_SRST is used to set the digital logic and the capacitors to a predetermined configuration at startup.

When CTL\_MODE\_P transitions low, and the output of flip-flop 80 remains high, AND gate 82 outputs a pulse OP\_ZPR, which indicates that the PVT oscillator controller 24 has just completed its task. Further, when CTL\_MODE\_P transitions low, multiplexer 72 passes the output of flip-flop 76; hence DCO\_IN\_P remains static.

A circuit essentially identical to the PVT-oscillator interface and phase restart circuit 70 is also provided in the acquisition oscillator controller 26 to indicate the end of the acquisition mode and to maintain the capacitors 18 of array 14b in their final state. The acquisition oscillator interface and phase restart generation circuit for the acquisition oscillator controller 26 outputs a signal OA\_ZPR when the acquisition mode is finished.

FIG. 14 illustrates a block diagram of phase error restart circuit 84, which can be part of the reference accumulator 62. Under normal operation, FCW (frequency control word) is accumulated by adder 86. On each CKR clock, the accumulated FCW passes through multiplexer 88 and is stored in register 90. The output of register 90 is returned to adder 86, which adds the accumulated FCW with the new FCW. The output is the phase reference (PHR), shown in FIGS. 12b and 12c. However, upon startup (CTL\_SRST is high), or end of a mode (OP\_ZPR is high at the end of the PVT mode or OA\_ZPR is high at the end of the acquisition

mode), the output of OR gate 94 controls multiplexer 88 to pass a value equal to FCW+PHV\_SMP-PHF (with proper bit alignment). This value will be the new PHR at the end of the PVT mode, the end of the acquisition mode or at startup.

5 Referring again to FIGS. 12b and 12c, it can be seen that the output value of the phase detection circuit 60 is PHE=PHR+PHF-PHV\_SMP (with proper bit alignment). Substituting the re-calculated end-of-mode value for PHR, PHE=FCW+PHV\_SMP-PHF+PHF-PHV\_SMP=FCW. Hence, PHE at the beginning of a new mode will be set to FCW or as close to zero as possible.

FIG. 15 illustrates a preferred embodiment of a telecommunication device 100 using the frequency synthesizer 10. A baseband controller 102 is coupled to a memory 104 and a digital RF transceiver 106, which includes the RF transmitter 10 described above. The RF transmitter 10 may include any combination of the improvements described in detail above to improve the quality of the output.

Although the Detailed Description of the invention has been directed to certain exemplary embodiments, various modifications of these embodiments, as well as alternative embodiments, will be suggested to those skilled in the art. The invention encompasses any modifications or alternative embodiments that fall within the scope of the claims.

What is claimed is:

- 1. A frequency synthesizer, comprising:
  - a digitally controlled oscillator, including a plurality of switched capacitors; control circuitry for selectively enabling and disabling said capacitors responsive to an oscillator tuning word, comprising:
    - select circuitry for enabling a number of capacitors responsive to said oscillator tuning word;
    - circuitry for dynamically varying which capacitors are enabled for a given oscillator tuning word to reduce non-linearities caused by slight variances in capacitive values.
- 2. A method of synthesizing a frequency, comprising the steps of:
  - selectively enabling and disabling capacitors in a digitally controlled oscillator responsive to an oscillator tuning word; and
  - circuitry for dynamically varying which capacitors are enabled for a given error signal value to reduce non-linearities caused by slight variances in capacitive values.

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