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**Perreault et al.**

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(54) **LINEARITY AND NOISE IMPROVEMENT FOR MULTILEVEL POWER AMPLIFIER SYSTEMS USING MULTI-PULSE DRAIN TRANSITIONS**

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(71) Applicant: **Eta Devices, Inc.**, Cambridge, MA (US)

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CPC ..... H04B 1/04; H03F 1/04; H03F 1/02; H03F 3/68; H03F 1/025; H03F 3/60; H03F 3/20;  
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(72) Inventors: **David J. Perreault**, Andover, MA (US); **Joel L. Dawson**, Roslindale, MA (US); **Wei Li**, Monterey, CA (US); **Yevgeniy A. Tkachenko**, Belmont, MA (US); **Balaji Lakshminarayanan**, Woburn, MA (US); **John Hoversten**, Lafayette, CO (US)

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(73) Assignee: **Eta Devices, Inc.**, Cambridge, MA (US)

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*Primary Examiner* — Pablo Tran

(74) *Attorney, Agent, or Firm* — Daly, Crowley, Mofford & Durkee, LLP

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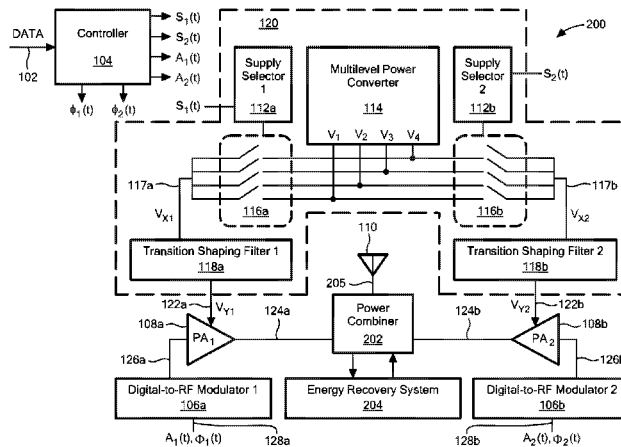
**Related U.S. Application Data**

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(57) **ABSTRACT**

Described embodiments provide a radio frequency (RF) amplifier system having at least one amplifier. The at least one amplifier includes an RF input port, an RF output port and a drain bias port. At least one voltage modulator is coupled to the bias port of the least one amplifier to provide a bias voltage. The bias voltage is selected by switching among a plurality of discrete voltages. At least one filter circuit is coupled between the at least one voltage modulator and the at least one amplifier. The at least one filter circuit controls spectral components resultant from transitions in

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the bias voltage when switching among the plurality of discrete voltages. A controller dynamically adapts at least one setting of the at least one voltage modulator by using multi-pulse transitions when switching among the plurality of discrete voltages for a first operating condition of the RF amplifier.

**25 Claims, 12 Drawing Sheets**

**Related U.S. Application Data**

is a continuation of application No. 14/666,965, filed on Mar. 24, 2015, now Pat. No. 9,209,758, which is a continuation of application No. 14/338,671, filed on Jul. 23, 2014, now Pat. No. 9,020,453.

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 See application file for complete search history.

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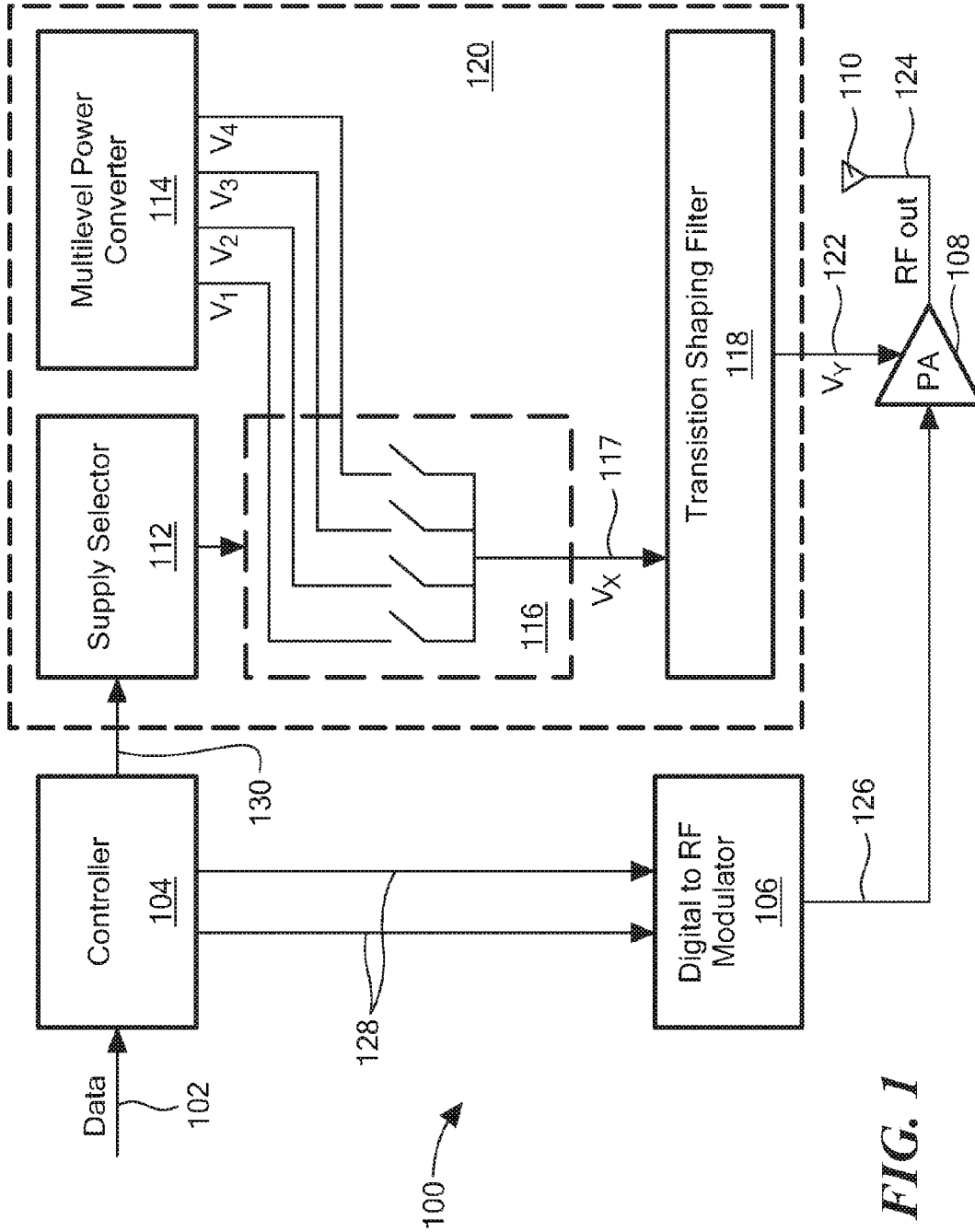


FIG. 1

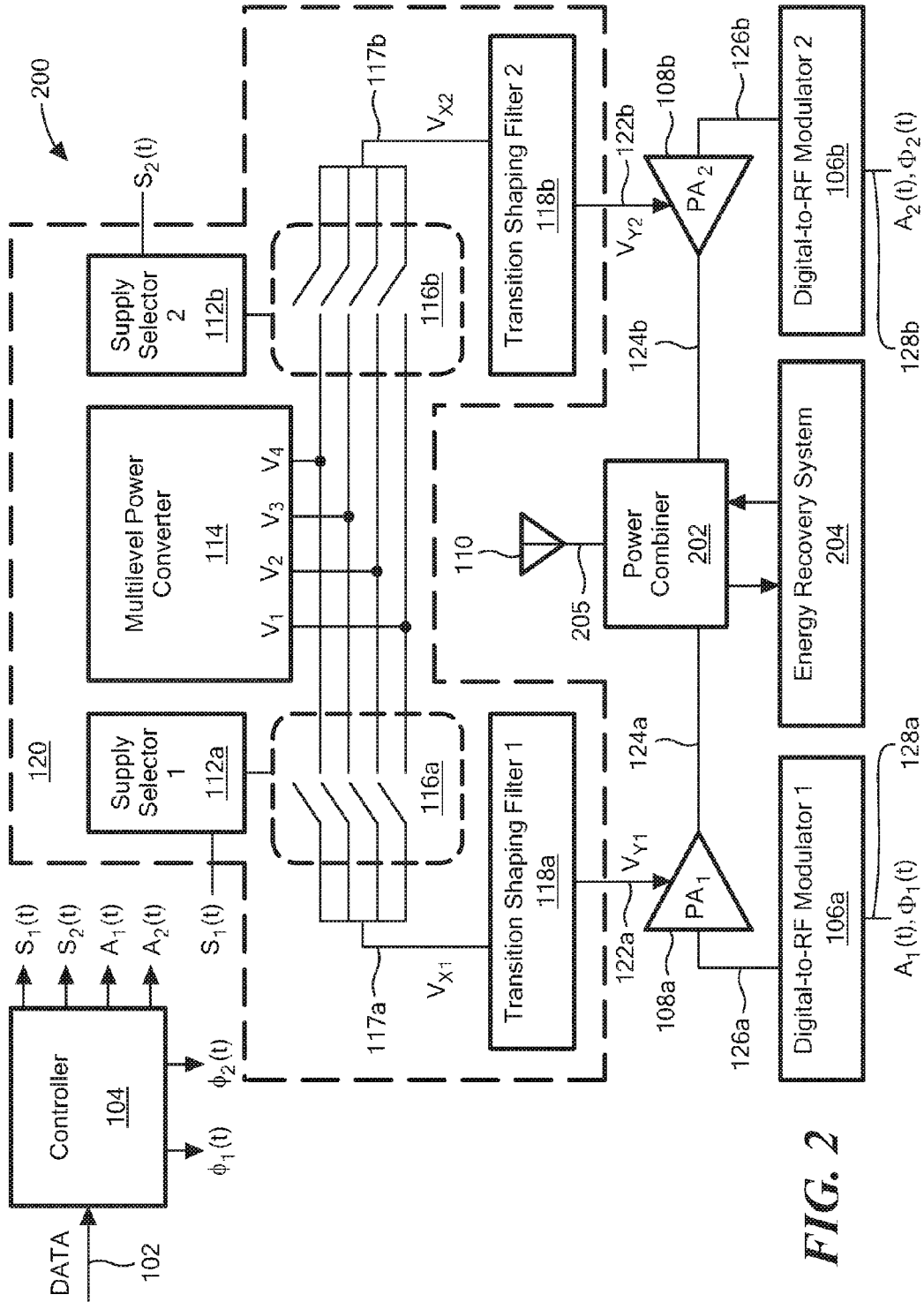


FIG. 2



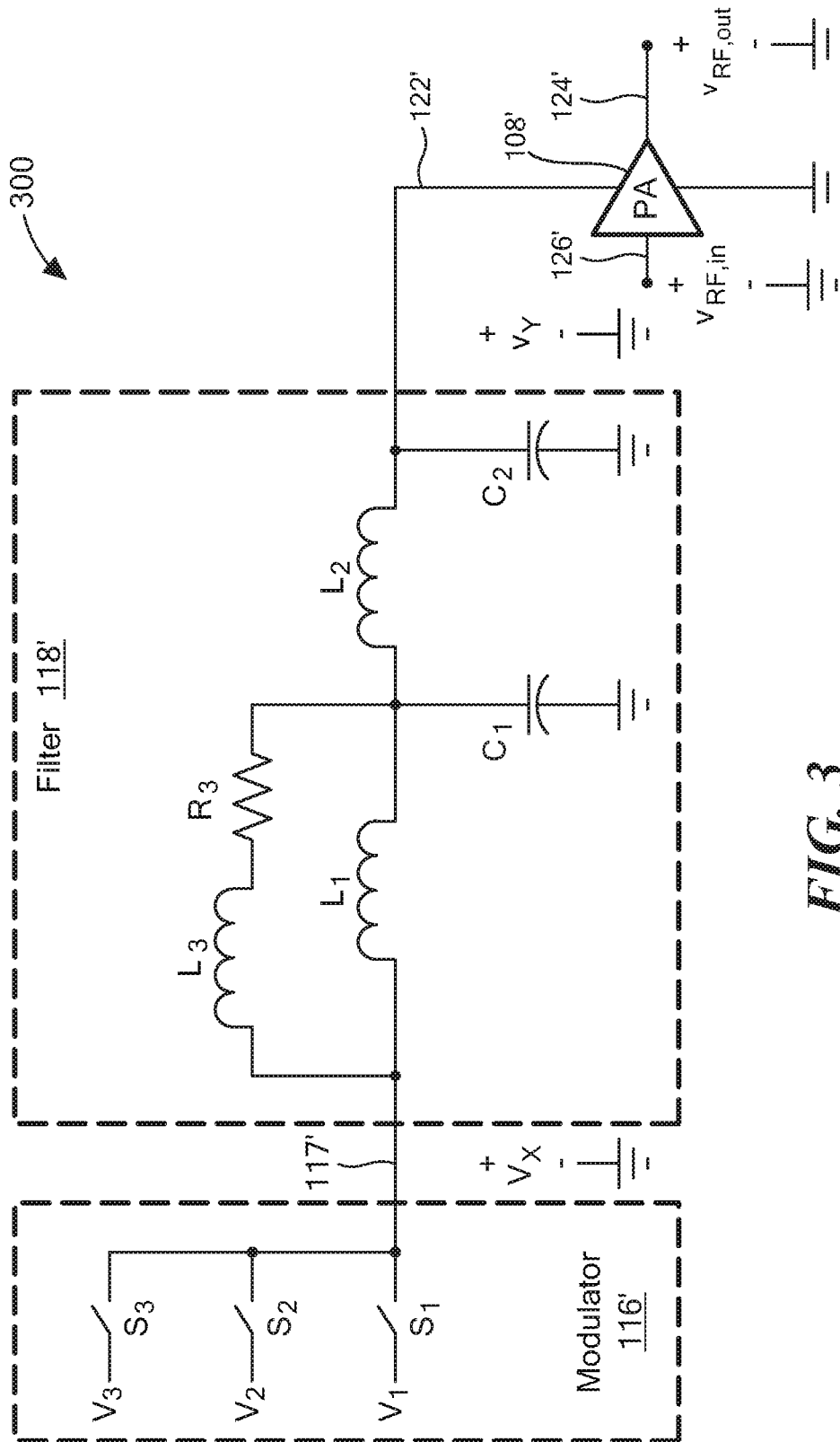
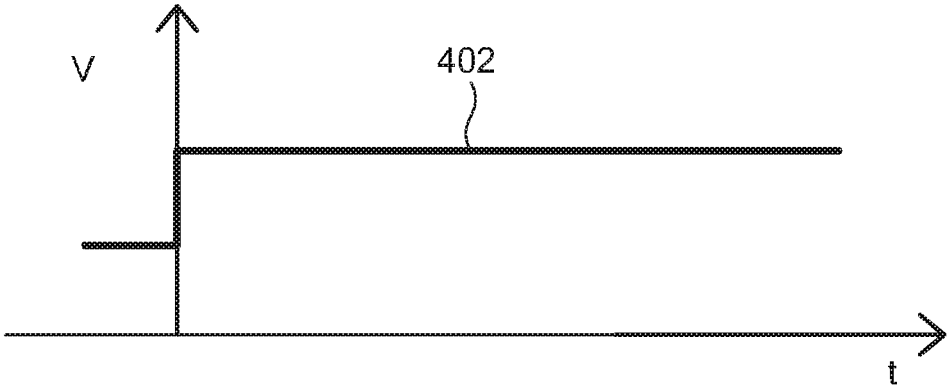
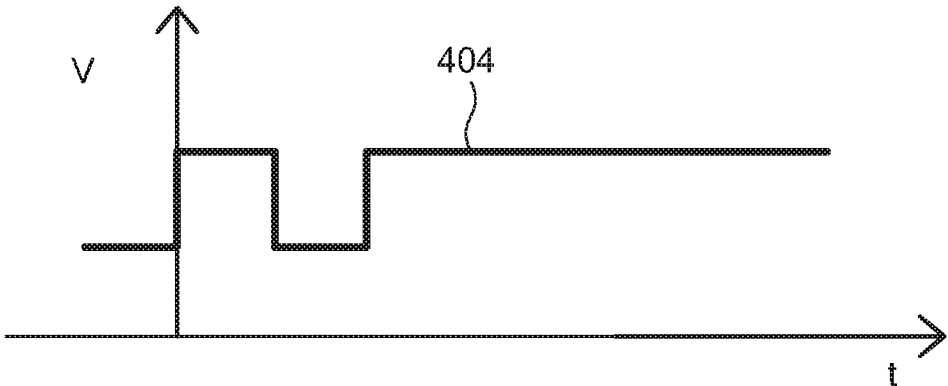


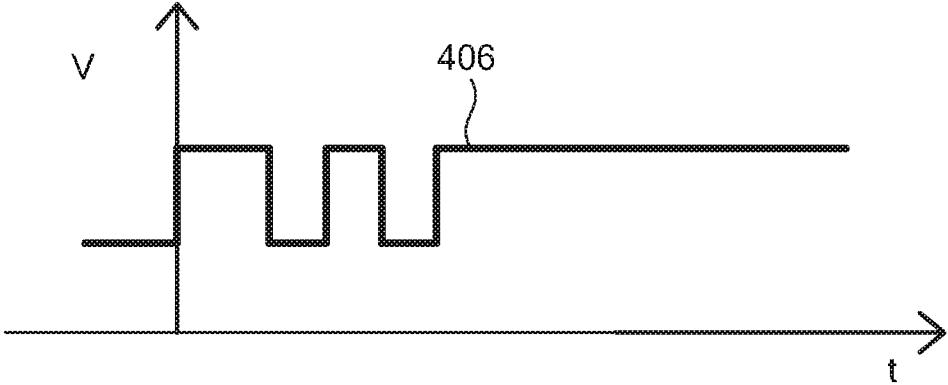
FIG. 3



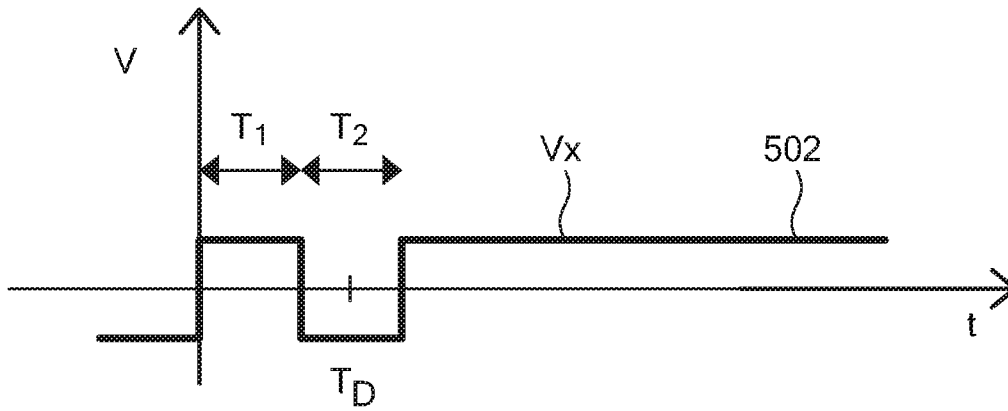
*FIG. 4A*



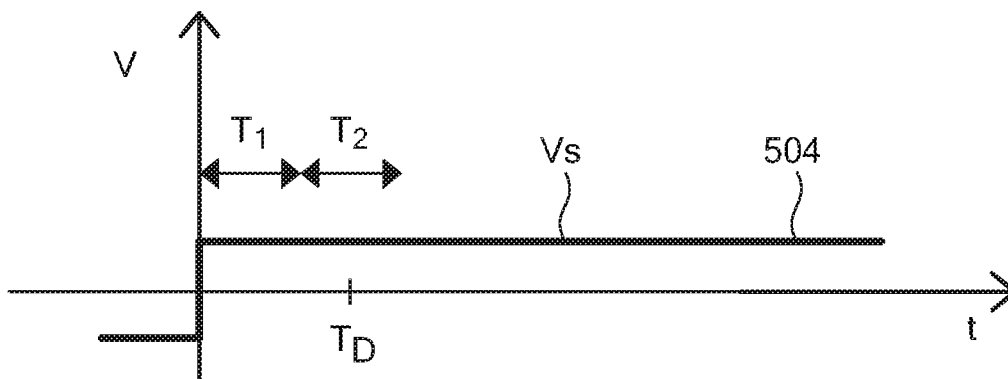
*FIG. 4B*



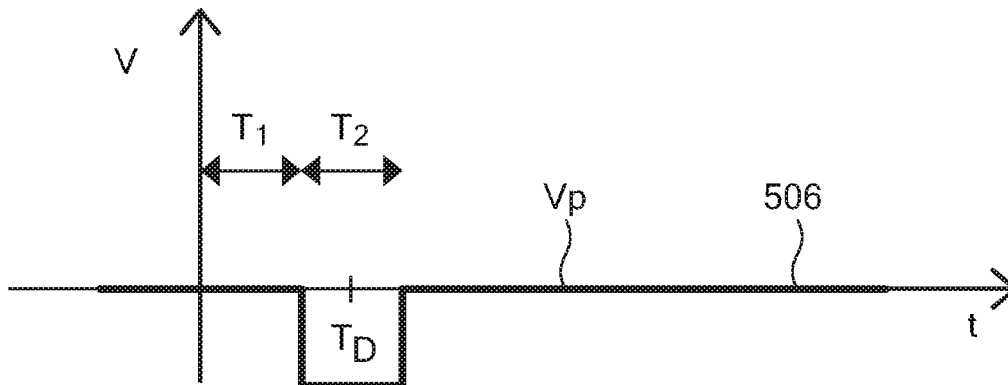
*FIG. 4C*



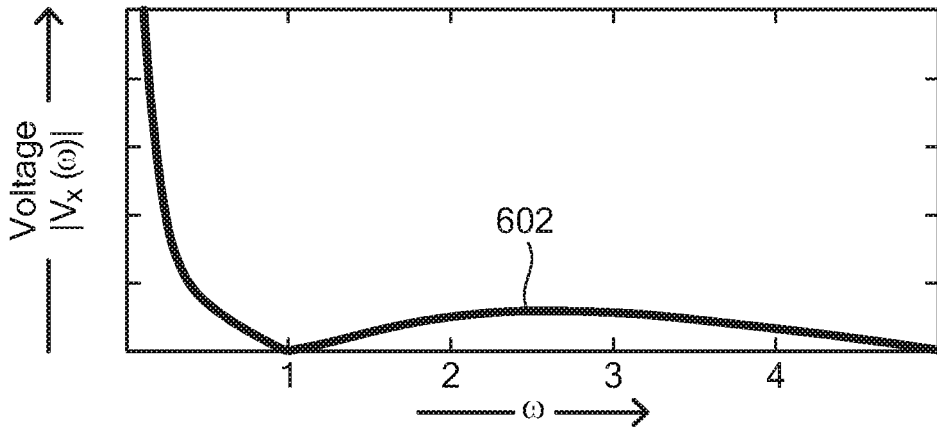
**FIG. 5A**



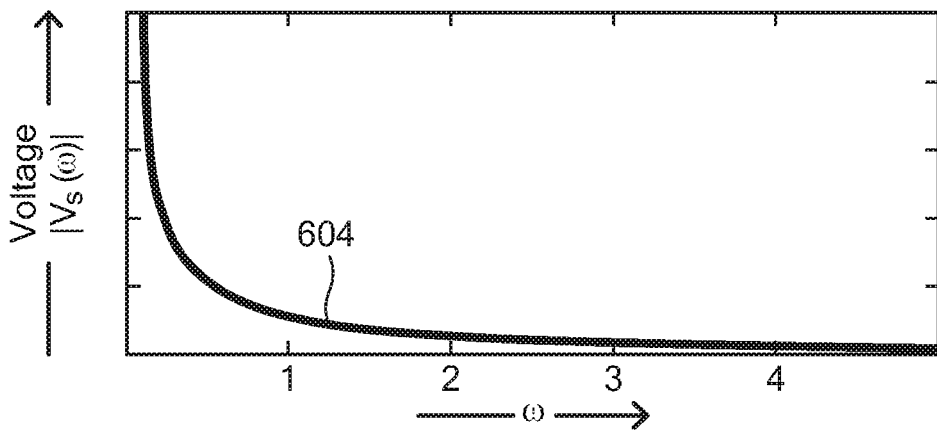
**FIG. 5B**



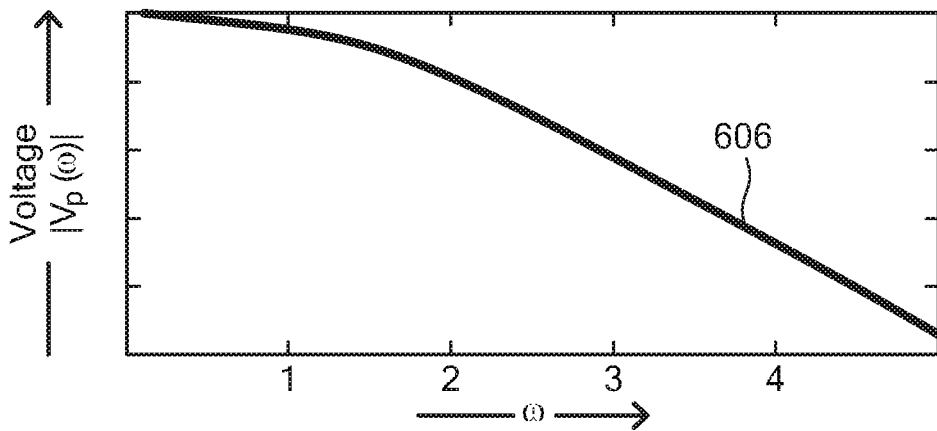
**FIG. 5C**



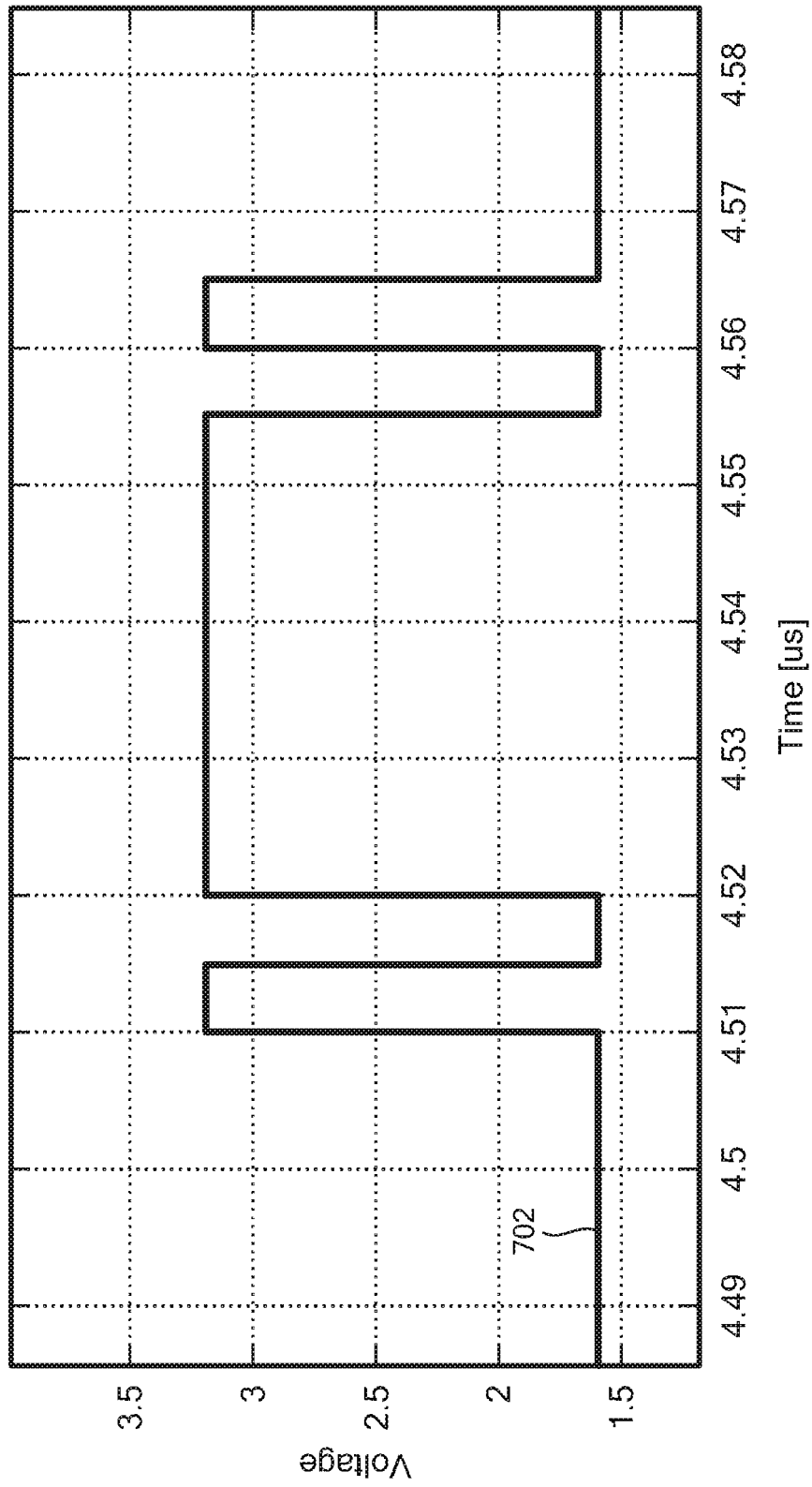
*FIG. 6A*



*FIG. 6B*



*FIG. 6C*



**FIG. 7A**

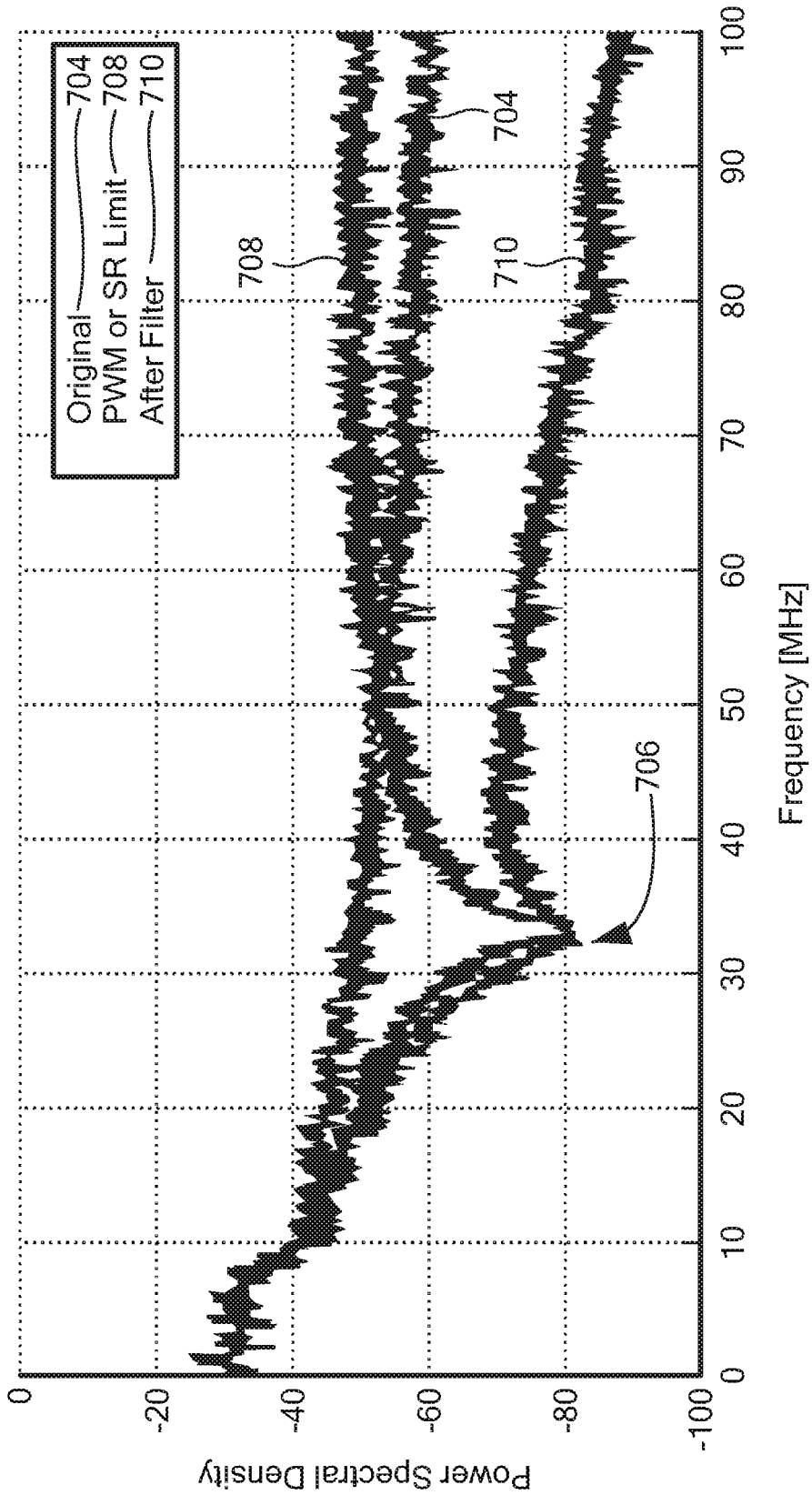


FIG. 7B

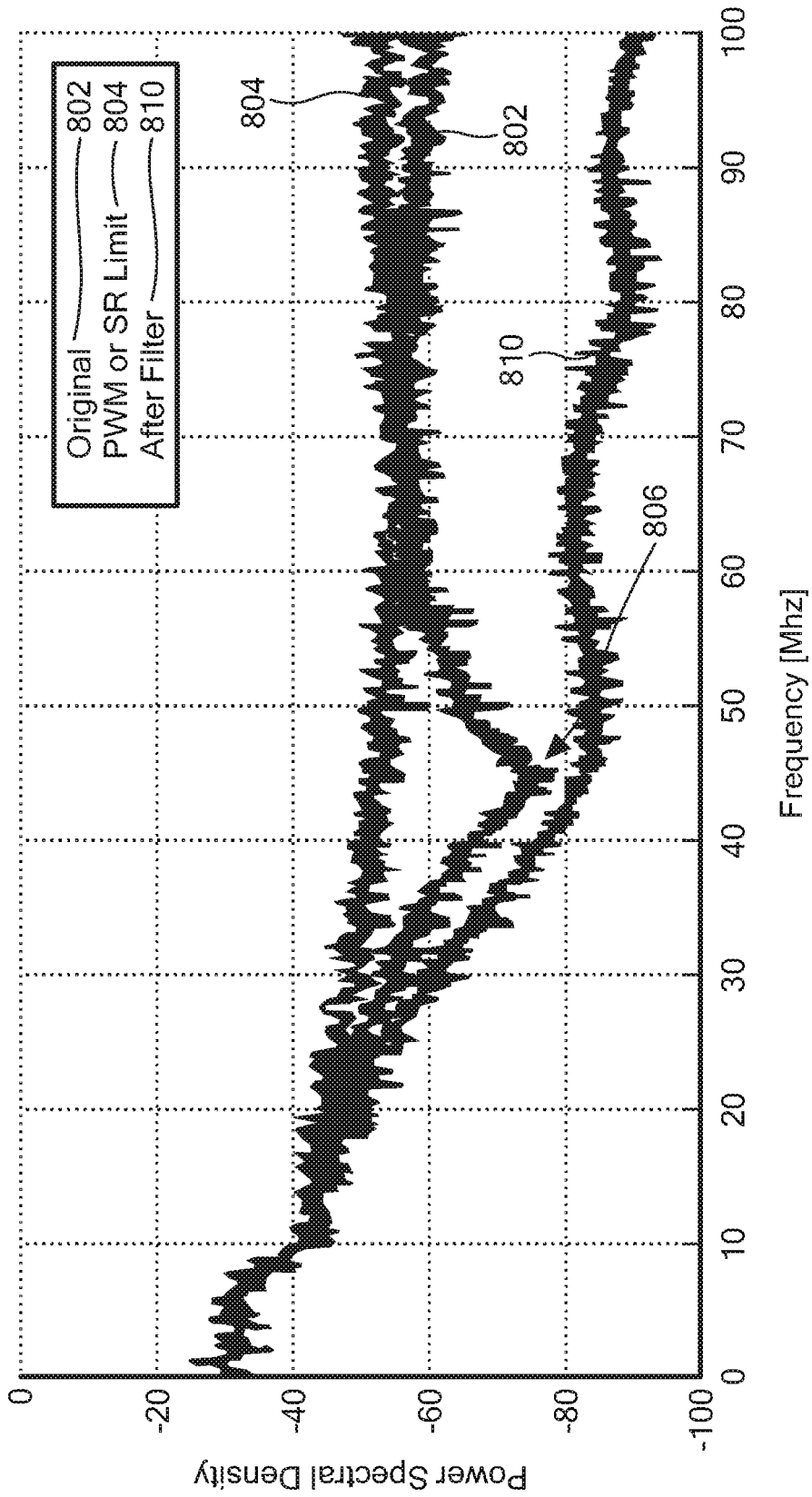


FIG. 8

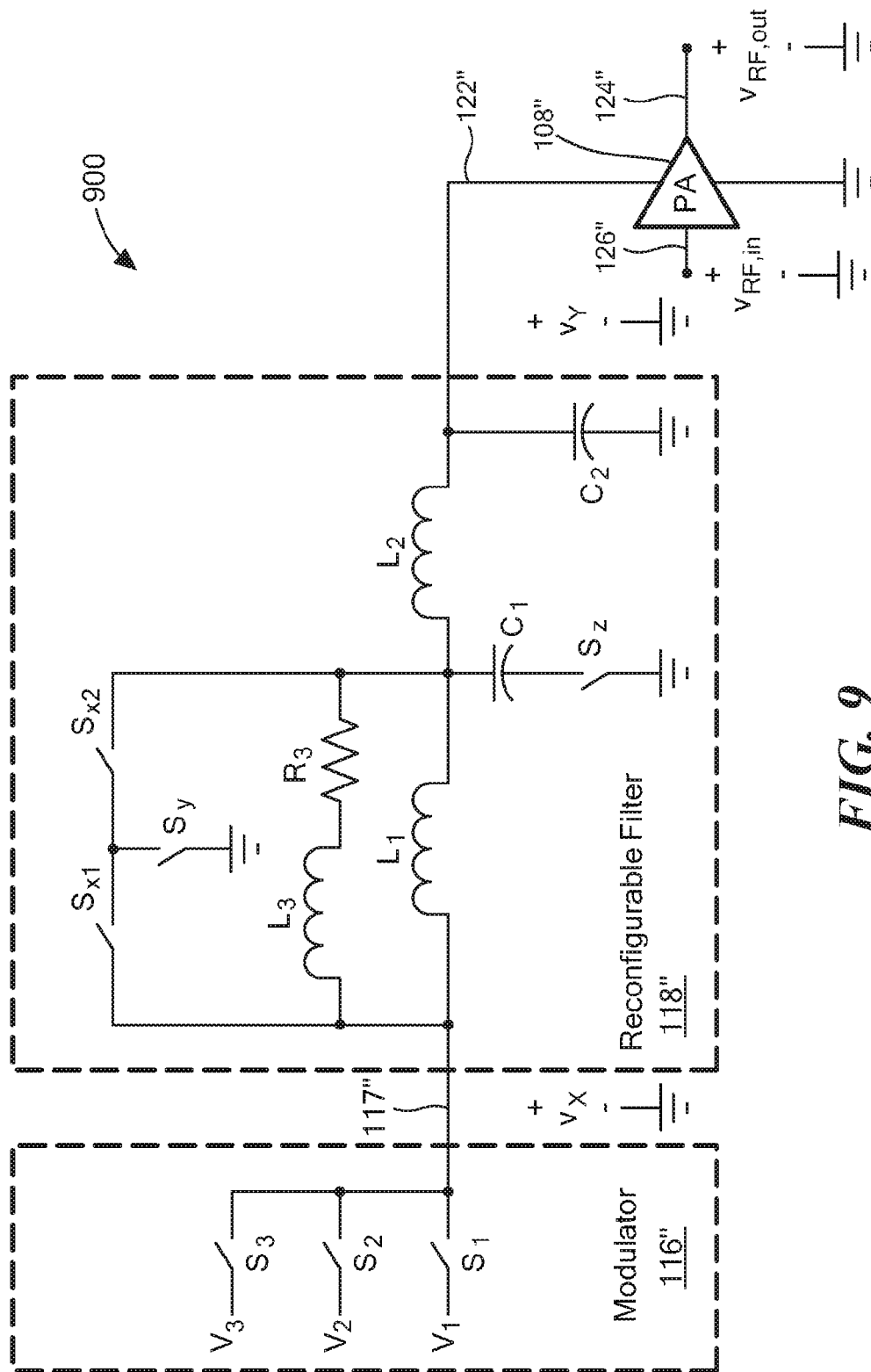


FIG. 9



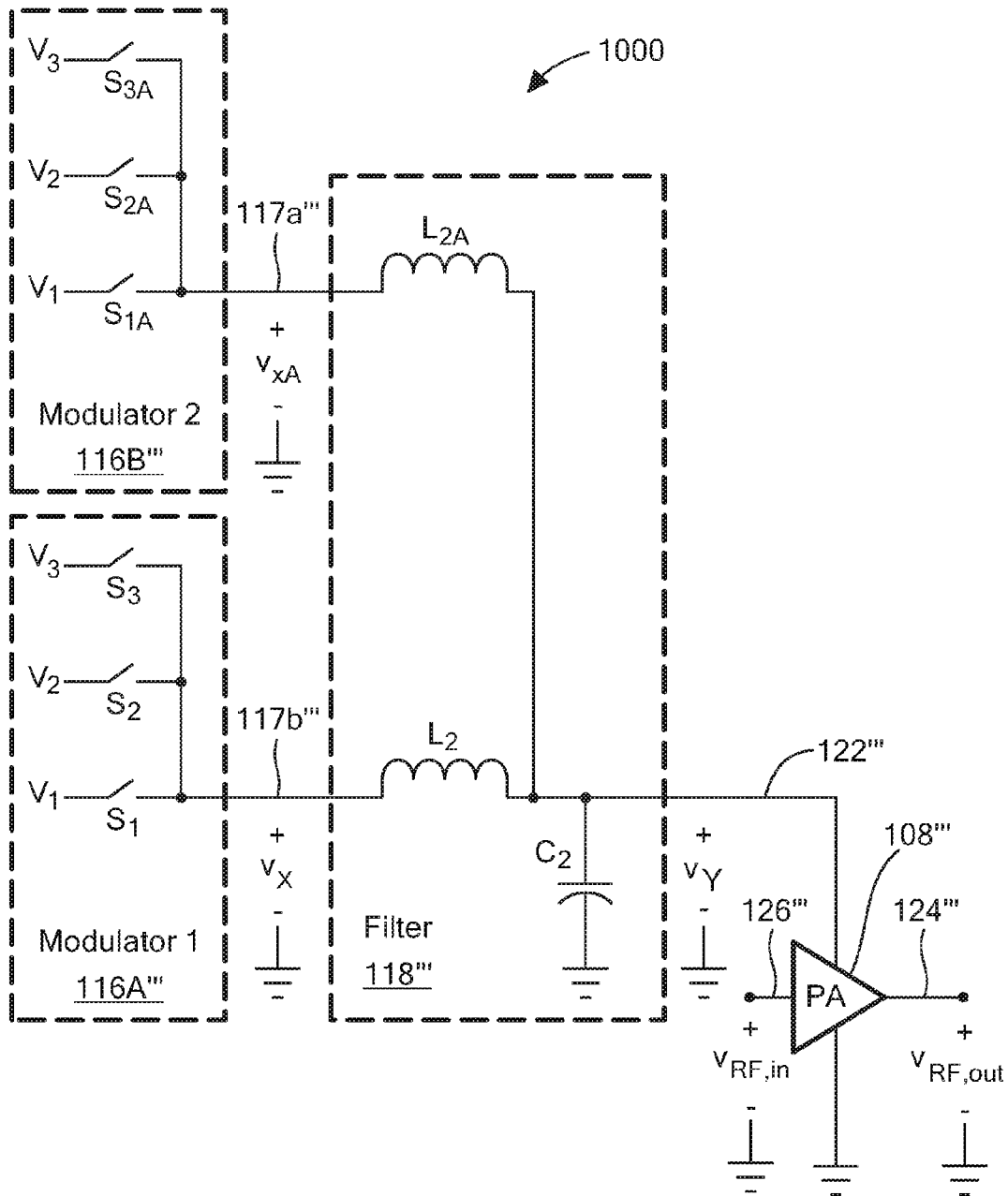


FIG. 10

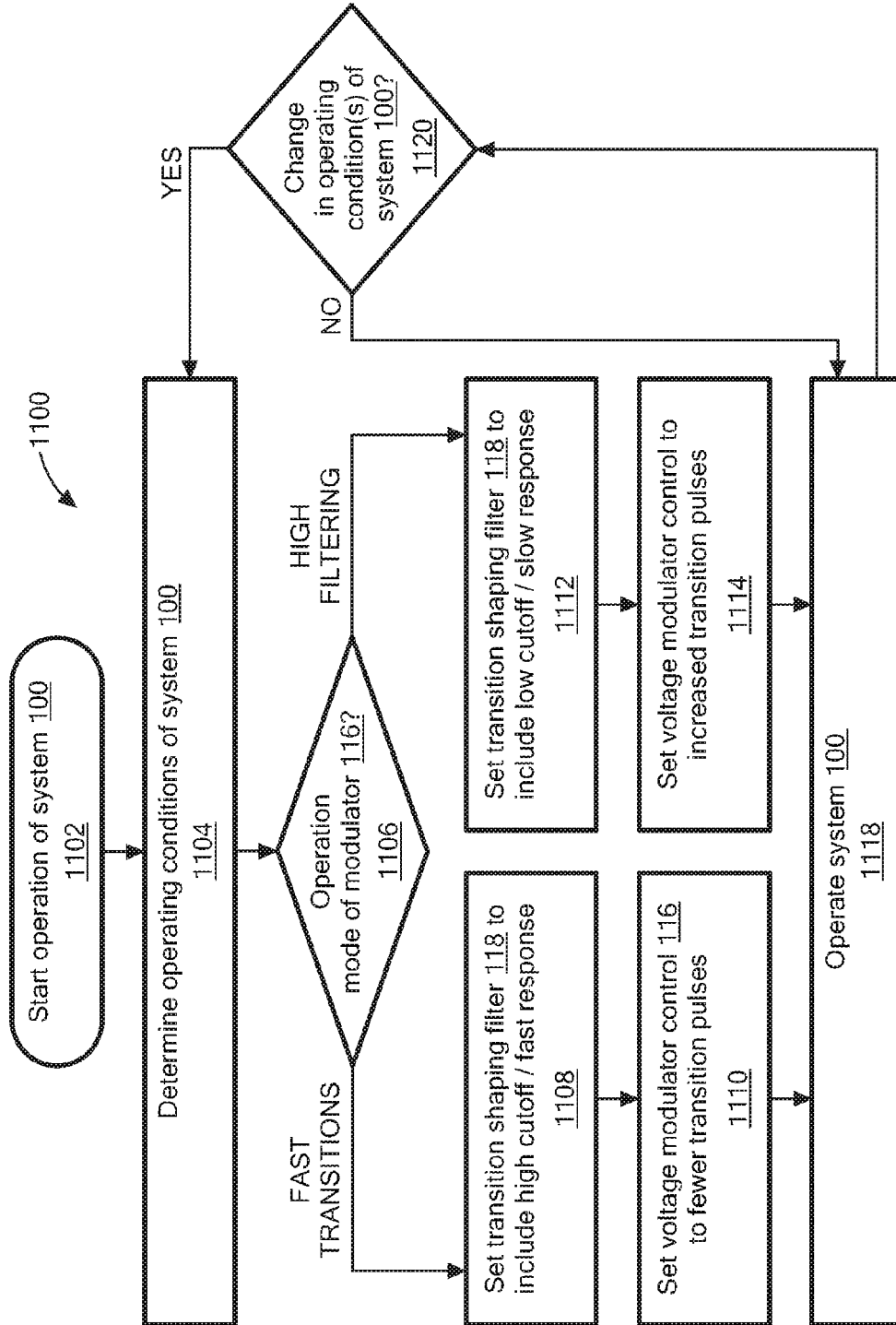


FIG. 11

1

**LINEARITY AND NOISE IMPROVEMENT  
FOR MULTILEVEL POWER AMPLIFIER  
SYSTEMS USING MULTI-PULSE DRAIN  
TRANSITIONS**

CROSS-REFERENCE TO RELATED  
APPLICATIONS

This application claims the benefit under 35 U.S.C. §119 (e) of U.S. provisional application No. 62/091,730, filed on Dec. 15, 2014, which is hereby incorporated herein by reference in its entirety.

This application is a continuation-in-part, and claims the benefit under 35 U.S.C. §120, of U.S. patent application Ser. No. 14/934,760 filed Nov. 6, 2015, which is a continuation of U.S. patent application Ser. No. 14/666,965 filed Mar. 24, 2015, now issued as U.S. Pat. No. 9,209,758, which is a continuation of U.S. patent application Ser. No. 14/338,671 filed Jul. 23, 2014, now issued as U.S. Pat. No. 9,020,453, which are hereby incorporated herein by reference in their entireties.

BACKGROUND

As is known in the art, achieving both high efficiency and high linearity of radio frequency (RF) power amplifier (PA) systems is a longstanding challenge. One means of improving efficiency in such systems is to utilize an architecture in which the PA system is switched with discrete transitions among a set of operating states (e.g., a set of drain bias voltages for one or more power amplifiers in the PA system). This includes systems where the drain voltage of at least one power amplifier is selected (e.g., via switches) from among multiple discrete supply voltages. Discrete output states can also be realized through systems in which the drain voltage is derived from a direct current (DC) voltage source, such as a DC-DC converter that has a plurality of preferred discrete output voltage levels (with the converter output network and/or a filter optionally providing for shaping of transitions between those preferred levels). Other means of synthesizing a set of discrete output levels can likewise be realized.

The nature of the drain voltage transitions in such systems can be important to the RF output quality that is achieved. In particular, the power amplifiers respond to both changes in the RF (gate) input and their DC bias (drain) input.

As is also known, high frequency (e.g., RF) signal components can occur due to changes in a drain voltage and such signal components can be “mixed” (e.g., cross-coupled) with the RF input, yielding undesirable switching signal components in the RF output spectrum around the carrier frequency. However, it is difficult to compensate for such high-frequency drain voltage components via controlling the RF inputs to the PA system. Such undesired components in the RF output might lead to leakage into adjacent channels thereby reducing “linearity” through worsening of “Adjacent Channel Leakage Ratio” (ACLR). Moreover, such undesired components in the RF output can appear in the receive band, contributing to receive-band noise and reducing receiver performance.

Designing multilevel power amplifier systems to mitigate these unwanted spectral components is a challenging task that imposes significant design constraints (e.g., on the range of conditions for which a particular system can operate well.) It is particularly challenging to design such systems to operate well across a wide range of bandwidths and/or in different bands (e.g., with different receive-band spacing and

2

placement) and/or for both time-division duplexing (TDD) and frequency-division duplexing (FDD).

SUMMARY

Described embodiments are generally directed toward a radio frequency (RF) amplifier system having at least one amplifier. The at least one amplifier includes an RF input port, an RF output port and a drain bias port. At least one voltage modulator is coupled to the bias port of the least one amplifier to provide a bias voltage. The bias voltage is selected by switching among a plurality of discrete voltages. At least one filter circuit is coupled between the at least one voltage modulator and the at least one amplifier. The at least one filter circuit controls spectral components resultant from transitions in the bias voltage when switching among the plurality of discrete voltages. A controller dynamically adapts at least one setting of the at least one voltage modulator by using multi-pulse transitions when switching among the plurality of discrete voltages for a first operating condition of the RF amplifier.

This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used to limit the scope of the claimed subject matter.

BRIEF DESCRIPTION OF THE DRAWING  
FIGURES

Other aspects, features, and advantages of the claimed invention will become more fully apparent from the following detailed description, the appended claims, and the accompanying drawings in which like reference numerals identify similar or identical elements. Reference numerals that are introduced in the specification in association with a drawing figure may be repeated in one or more subsequent figures without additional description in the specification in order to provide context for other features.

FIG. 1 is a block diagram of a multilevel radio frequency (RF) power amplifier (PA) system in accordance with illustrative embodiments;

FIG. 2 is a block diagram of a multilevel RF PA system in accordance with illustrative embodiments;

FIG. 3 is a schematic diagram of a multilevel RF PA system with a drain-voltage modulator and filter in accordance with illustrative embodiments;

FIGS. 4A, 4B and 4C are timing diagrams showing a series of plots of voltage versus time for switching voltage waveform patterns for transitions among operating states of a PA in accordance with illustrative embodiments;

FIGS. 5A, 5B and 5C are timing diagrams showing a series of plots of voltage versus time for control signals transitioning among operating states of a PA in accordance with illustrative embodiments;

FIG. 6A is a plot of frequency versus time showing frequency-domain voltage magnitude content associated with the voltage transitions caused by the control signal of FIG. 5A;

FIG. 6B is a plot of frequency versus time showing frequency-domain voltage magnitude content associated with the voltage transitions caused by the control signal of FIG. 5B;

FIG. 6C is a plot of frequency versus time showing frequency-domain voltage magnitude content associated with the voltage transitions caused by the control signal of FIG. 5C;

3

FIG. 7A is a plot of voltage versus time showing a time-domain voltage response of a drain modulation waveform for a first operating state of the PA system shown in FIG. 3;

FIG. 7B is a plot showing power spectral density of the filtered output for a first operating state of the PA system shown in FIG. 3;

FIG. 8 is a plot showing power spectral density of the filtered output for a first operating state of the PA system shown in FIG. 3;

FIG. 9 is a schematic diagram of an illustrative multilevel power amplifier system having a reconfigurable transition filter;

FIG. 10 is a schematic diagram of an illustrative multilevel power amplifier system having multiple drain voltage modulators and a multiple-input, single-output transition filter; and

FIG. 11 is a flow diagram of a voltage modulation technique in accordance with illustrative embodiments.

#### DETAILED DESCRIPTION

The concepts, circuits, systems and techniques described herein reduce or suppress (ideally eliminate) undesired output signal components in multilevel radio frequency (RF) amplifier systems, and in particular in multilevel RF power amplifier (PA) systems. Embodiments using such concepts, circuits, systems and techniques might have, for example, improved linearity and reduced undesired RF output components (or “noise”) as well as receive-band noise. Described embodiments provide improved shaping of spectral components resulting from voltage transitions that might be introduced, for example, at the drain voltage of power amplifiers (PAs) of the RF system. For example, PA systems might desirably transition among one or more discrete states (e.g., discrete voltage states at which the PAs operate to provide a given output signal) for some operating conditions. Illustrative PA systems are described in U.S. Pat. No. 8,829,993, U.S. Pat. No. 9,020,453, and U.S. Pat. No. 8,824,978, all owned by the assignee of the present application, and which are hereby incorporated herein by reference in their entireties.

Additionally or alternatively, PA systems might provide continuous envelope tracking or adaptive power tracking for other conditions. This might be accomplished by (1) switching a drain bias signal from one of a set of discrete supplies to an input that provides continuous envelope tracking, (2) changing from a mode where one voltage is selected from among individual levels to a mode that rapidly pulse-width modulates (PWM) among the voltage levels to provide a continuously variable output for envelope tracking, or (3) adapting the set of discrete drain bias voltages over time. PA systems that adapt discrete drain bias voltages over time are described in U.S. patent application Ser. No. 14/035,445 filed on Sep. 24, 2013, Ser. No. 14/619,737 filed Feb. 11, 2015, Ser. No. 14/837,616 filed Aug. 27, 2015, and Ser. No. 14/255,427 filed Apr. 17, 2014, all owned by the assignee of the present application, and which are hereby incorporated herein by reference in their entireties.

The concepts, circuits, systems and techniques described herein might commonly be employed, for example, in “class G” amplifiers, a Multi-level Linear amplifier with Nonlinear Components (MLINC), Asymmetric Multilevel Outphasing (AMO) amplifiers, and multilevel backoff amplifiers including Asymmetric Multilevel BackOff (AMBO) amplifiers.

Described embodiments achieve a high degree of linearity and low noise during operating state switching of the power

4

amplifier (PA), and provide flexibility to address a wide variety of different operating conditions (e.g., different bandwidths, transmission bands, etc.) that impose different requirements on drain bias voltage transitions.

Referring now to FIG. 1, illustrative PA system 100 includes one or more RF amplifiers, shown here as power amplifier (PA) 108 that receives a drain bias signal 122 that is dynamically selected from among a number of discrete signal levels, shown here as  $V_1$ - $V_4$ . Transition shaping filter 118 controls (e.g., smooths or otherwise shapes via filtering) the transitions between the levels as will be described below. PA system 100 further includes controller 104 that processes data 102 for transmission by the PA system. Controller 104 processes data 102 and provides data and control signals 128 to digital-to-RF modulator 106 and control signals 130 to supply modulator (or drain bias circuit) 120. In response to signals provided from controller 104, digital-to-RF modulator 106 provides a modulated RF signal 126 to PA 108, which amplifies the signal provided thereto and provides an amplified RF signal 124 to antenna 110 for transmission. Illustrative PA system 100 might be employed in an RF receiver, transmitter or transceiver circuit, for example in a wireless communication system.

Controller 104 determines the drain bias voltage (e.g., drain bias signal 122) to be provided to PA 108. Controller 104 is also coupled to supply modulator 120. In response to signals provided from controller 104, supply modulator 120 provides a bias signal 122 having a determined voltage level to PA 108. In some embodiments, the supply modulator might optionally include supply selector 112 that actuates commands provided thereto from controller 104 (e.g., supply selector 112 might decode signals sent by controller 104). In other embodiments, controller 104 might provide control signals 130 directly to switches 116.

Regardless of particular manner in which controller 104 is coupled to supply modulator 120, bias signal 122 might be dynamically switched (e.g., modulated) among different power supply levels (e.g., voltage levels) based, at least in part, on characteristics of a signal to be transmitted (e.g., desired characteristics of RF output signal 124 to be transmitted via antenna 110). Bias signal 122 might be a selected one of a plurality of fixed supply voltages, for example supply voltages  $V_1$ ,  $V_2$ ,  $V_3$ , and  $V_4$  generated by multilevel power converter 114, and selected by switches 116 based on control signals from controller 104. Alternatively, bias signal 122 might be dynamically varied (e.g., if multilevel power converter 114 is a variable output supply). Similarly, the supply voltages  $V_1$ ,  $V_2$ ,  $V_3$ , and  $V_4$  shown in FIG. 1 might be themselves dynamically varied. Thus, the supply voltage applied to PA 108 might be varied based on characteristics of the signal to be transmitted, for example, a desired average power level during a particular time period.

In some embodiments, the switched power supply levels might be directly applied to PA 108 (e.g., as bias signal 122), or might be coupled to PA 108 through transition shaping filter 118, which filters or otherwise removes undesired switching signal characteristics (e.g., sharp transition edges or other switching noise) to provide acceptable transitions among the power supply levels.

For example, sharp transition edges or other noise present on the power supply input to the power amplifier (collectively referred to as switching noise) might be coupled into the RF output of the power amplifier (e.g., into RF output signal 124).

Filter 118 might be provided as a passive filter (including passive components such as resistors, inductors and capacitors), an active filter (including active components such as

transistors, transistor switches, switches and amplifiers), or a hybrid filter (including a combination of passive and active components). It should be appreciated that, for some applications, system **100** might be implemented in a single integrated circuit (IC).

Referring now to FIG. 2, illustrative PA system **200** includes a pair of RF amplifiers **108a** and **108b** (here illustrated as power amplifiers), which each receive a bias signal **122a** and **122b** from supply modulator (or drain bias circuit) **120**. Supply modulator **120** provides bias signals **122a** and **122b** having values (e.g., voltage levels) dynamically selected depending upon one or more characteristics of the signal to be transmitted. As shown in FIG. 2, power supply levels are provided to multiple PAs, shown in FIG. 2 as PA1 **108a** and PA2 **108b**.

It should be appreciated that although illustrative system **200** is shown as having two amplifiers **108a** and **108b**, any number of amplifiers (e.g., PAs) might be employed. The power supply levels might be independently modulated (e.g., by switches **116** based on control signals from controller **104**) among different bias levels (e.g., drain voltage levels, for example voltages  $V_1, V_2, V_3, V_4$ ), which might be fixed or variable over time.

Likewise, the transitions among the different voltage levels  $V_1, V_2, V_3, V_4$  might be shaped by transition shaping filters **118a** and **118b** to provide improved radio frequency (RF) output characteristics of PAs **108**. For example, by reducing (or ideally, removing) switching noise (including undesired switching signal components of the transitions, noise from parasitics excited by switching or other noise from the power converter, etc.) from the power supply input and, thus, preventing switching noise from being coupled to the RF output(s) (e.g., **124a** and **124b**) of the PA. The characteristics of filters **118a** and **118b** are thus selected to reduce, and ideally prevent, switching noise from being introduced to the RF transmit signal path (e.g., RF output signal **124**) via respective bias terminals of amplifiers **108a** and **108b**. It is desired that the filters have a passband that is wide enough (in frequency) to accommodate sufficiently rapid drain bias changes for the PAs to efficiently transmit the desired output signal at the needed bandwidth, but provide sufficient attenuation at higher frequencies such that components in the filtered drain bias signal will not cause out-of-band interference (e.g., in the receive band). In many embodiments, it is desired to have a response that is also fast (responding quickly to a level change) but reasonably well damped.

It should be appreciated that although each amplifier **108a** and **108b** are shown in FIG. 2 as having unique corresponding elements (e.g., supply selector **112a**, switches **116a**, transition shaping filter **118a** and modulator **128a** for PA **108a**, and supply selector **112b**, switches **116b**, transition shaping filter **118b** and modulator **128b** for PA **108b**), systems might employ one or more common elements among the PAs **108**.

As also shown in FIG. 2, the outputs of amplifiers **108a** and **108b** are combined by power combiner **202** to provide a single RF output to antenna **110**. In some embodiments, power combiner **202** might be an isolating power combiner or an isolating power combiner with an energy recovery system (e.g., **204**) coupled to the isolation port of the power combiner. The energy recovery module **204** might operate such as described in U.S. Pat. No. 8,830,710 assigned to the assignee of the present application and which is hereby incorporated herein by reference in its entirety. Alternatively, power combiner **202** might be a non-isolating combiner, such as a Doherty combiner, a Chireix combiner, or

with another combiner comprising combinations of transmission line(s) and/or energy storage element(s). Thus, power combiner **202** generates a single high-power output for transmission by antenna **110** based on the output of amplifiers **108a** and **108b**.

In other embodiments, amplifiers **108a** and **108b** might support separate RF outputs (e.g., for a MIMO system or for a balanced power amplifier system utilizing multiple PAs), for example with each amplifier **108a** and **108b** feeding a separate antenna **110** versus being combined into a single output via power combiner **202**. In other embodiments, one subset of amplifiers might serve as a driver stage for another subset of amplifiers.

Multilevel power converter **114** might be powered from a single input, with the power supply voltages generated in a variety of ways, for example, by employing a multi-output switched-capacitor power supply or a hybrid magnetic-switched-capacitor power supply such as described in U.S. patent application Ser. No. 14/035,445 filed on Sep. 24, 2013 assigned to the assignee of the present application and which is hereby incorporated herein in its entirety. Other embodiments might employ a multi-output magnetic converter (e.g., with multiple tapped inductors or multi-winding transformers or using a single inductor multiple output (SIMO) configuration), or employ individual power supplies to synthesize each of  $V_1, V_2, V_3$  and  $V_4$  from the single input. Likewise, one or more of the power supply levels might be taken from convenient voltages already available for other components in a given system. It will be appreciated that while four supply levels  $V_1, V_2, V_3$  and  $V_4$  are shown in FIG. 2, any desirable number of supply levels might be employed.

As shown in FIG. 2, controller **104** generates control signals  $S_1(t)$  and  $S_2(t)$  for respective supply selectors **112a** and **112b**. Control signals  $S_1(t)$  and  $S_2(t)$  are provided to supply modulator **120** and employed by supply selectors **112a** and **112b**, respectively, to configure switches **116a** and **116b** that modulate the power supply voltage provided to a corresponding one of PAs **108a** and **108b**. Control signals  $S_1(t)$  and  $S_2(t)$  vary over time based on data **102** input to controller **104**.

Controller **104** also generates control signals  $A_1(t), \phi_1(t), A_2(t)$  and  $\phi_2(t)$  for respective digital-to-RF modulators **106a** and **106b**. Control signals  $A_1(t)$  and  $A_2(t)$  are employed by digital-to-RF modulator **106a** and **106b**, respectively, to determine an amplitude of the output of the corresponding one of digital-to-RF modulators **106a** and **106b**. Control signals  $\phi_1(t)$  and  $\phi_2(t)$  are employed by digital-to-RF modulator **106a** and **106b**, respectively, to determine a phase of the output of the corresponding one of digital-to-RF modulator **106a** and **106b**. Control signals  $A_1(t), \phi_1(t), A_2(t)$  and  $\phi_2(t)$  can vary over time based on data **102** input to controller **104**. It will be appreciated that information denoted by signals  $A_1(t), \phi_1(t), A_2(t)$  and  $\phi_2(t)$  might be provided in any format that contains the information, including, for example, In-phase (I) and Quadrature (Q) signals, such as  $I_1(t), Q_1(t), I_2(t)$  and  $Q_2(t)$ .

Digital-to-RF modulators **106a** and **106b** modulate one or more local carriers based on information from control signals  $A_1(t), \phi_1(t), A_2(t)$  and  $\phi_2(t)$ , to generate RF signals **126a** and **126b**. RF signals **126a** and **126b** are provided to PAs **108a** and **108b**, respectively, to be amplified into RF output signals **124a** and **124b**, based upon the level of bias signals **122a** and **122b** provided to amplifiers **108a** and **108b**, respectively. RF output signals **124a** and **124b** are combined by power combiner **202** into a single RF output signal **205** that is transmitted by antenna **110**. It will be appreciated that an alternative approach (not shown) to providing signals

**126a** and **126b** to power amplifiers **108a** and **108b** would be to utilize a single digital-to-RF modulator **106a** (having an input from controller **104** specified as  $A_1(t)$ ,  $\phi_1(t)$ , or  $I_1(t)$ ,  $Q_1(t)$ ) and use an RF split of the output of digital-to-RF modulator **106a** to generate the two RF signals **126a** and **126b**. Such an approach is shown, for example, in U.S. patent application Ser. No. 14/920,031 filed on Oct. 22, 2015, assigned to the assignee of the present application and which is hereby incorporated herein in its entirety.

Thus, controller **104** sets, via control signals  $A_1(t)$ ,  $\phi_1(t)$ ,  $A_2(t)$  and  $\phi_2(t)$  (or their equivalents), the phase and amplitude of the RF input(s) provided to amplifiers **108a** and **108b**. Controller **104** further sets, by modulating the power supply level provided to amplifiers **108a** and **108b** via supply modulator **120**, the amplification provided by amplifiers **108a** and **108b** and, thus, the RF output power of the system that is transmitted by antenna **110** (e.g., signals **124**) to represent the data in signal **102**. Controller **104** might continuously modulate the power supply level provided to amplifiers **108a** and **108b**, for example, based upon one or more samples of data **102** (e.g., one or more data samples of the baseband data signal to be transmitted). For example, controller **104** might adjust the power supply level of amplifiers **108a** and **108b** based upon a window of  $N$  samples of data **102** and determine whether, for one or more of the samples in the window, the output power of the system (e.g., the power supply level of amplifiers **108a** and **108b**) should be adjusted.

Referring now to FIG. 3, a multilevel RF amplifier system **300** includes drain-voltage modulator **116'** and transition shaping filter **118'** supplying RF amplifier **108'**. Drain modulator **116'** modulates a bias voltage **122'** applied to a bias terminal of amplifier **108'** by switching voltages among multiple discrete voltage levels, shown in FIG. 3 as voltages  $V_1$ ,  $V_2$ , and  $V_3$ , to provide output voltage  $V_x$ . Transition shaping filter **118'** controls (e.g., smooths or otherwise shapes) transitions of output voltage  $V_x$  such that filter output voltage  $V_y$  provided as bias signal **122'** to PA **108'** has smooth transitions with high frequency content removed.

As shown in FIG. 3, some embodiments of drain modulator **116'** include as many switches (e.g., switches  $S_1$ ,  $S_2$  and  $S_3$ ) as there are input voltages (e.g.,  $V_1$ ,  $V_2$ , and  $V_3$ ). In other embodiments, the number of switches might differ from the number of voltages (e.g., there might be a lesser or greater number of switches than voltage levels). Drain modulator **116'** employs the switches to select a corresponding discrete input voltage level to provide as bias signal **122'** to PA **108'**. In some embodiments, switches **116'** are provided as semiconductor devices. In other embodiments, other voltage selection techniques might alternatively be used, for example, mechanical devices.

As shown in FIG. 3, transition shaping filter **118'** includes one or more filter stages of passive components (e.g., resistors, inductors and capacitors). For example, the embodiment shown in FIG. 3 includes a first filter stage including passive components  $L_1$ ,  $L_3$ ,  $R_3$  and  $C_1$ , and a second filter stage including passive components  $L_2$  and  $C_2$ . Although shown as including two filter stages, any number of filter stages might be employed. Passive components are beneficially employed as filter components since filters using passive components are simple, have high performance and are power efficient. However, active components could be used in addition or in the alternative to passive components.

In general, described embodiments prevent unwanted spectral content of signal **117'** from appearing in signal **122'** and mixing with the RF carrier, such that the frequency

content of injected noise from signal **117'** does not appear at an offset from the carrier frequency and/or the frequencies of signal **126'** at RF output signal **124'**. Stated differently, the spectral content of signal **122'** ( $v_y$ ) mixes with the RF carrier (or the content of signal **126'**) such that the frequency content of injected noise from  $v_y$  **122'** partly appears at an offset from the carrier frequency or from the content of signal **126'**. This portion of the frequency content of signal **124'** is reduced (and ideally removed) by transition shaping filter **118'**. In one embodiment, a high-order (e.g., two stage) filter is employed to substantially attenuate signal content above 30 MHz on the voltage **122'** supplied to PA **108'**. The cutoff frequency of the filter might be selected based upon the RF bandwidth required of a multilevel RF PA system (such as system **100** in FIG. 1 or system **300** in FIG. 3) such that any noise components present in the power supply provided to PA **108'** are sufficiently small, for example, such that the out-of-band noise of the RF output **124'** of PA system **300** does not interfere with or degrade the RF operation of the system (e.g., by putting noise at receive-band frequencies).

As shown in FIG. 3, voltage modulator **116'** includes switches  $S_1$ ,  $S_2$  and  $S_3$  that modulate a voltage  $v_x$  **117'**, provided to filter **118'**, among voltage levels  $V_1$ ,  $V_2$ , and  $V_3$ . Transition filter **118'** controls (e.g., shapes or smooths) sharp transitions in voltage  $v_x$  **117'** such that the voltage  $v_y$  **122'** provided to PA **108** has smooth transitions with reduced high-frequency content. In described embodiments, modulator **116'** and transition filter **118'** operate over a variety of operating conditions. For example, system **300** might operate under one or more of the following operating conditions: (1) an adaptive power tracking (APT) mode, in which the drain voltage need only be adapted slowly (e.g., by adjusting one or more of  $V_1$ ,  $V_2$ , and  $V_3$ , and/or by switching among them at a low rate); (2) time-division duplexing (TDD), in which the signal bandwidth is wide, necessitating a high rate of transitions among levels and with rapid response of voltage  $v_y$  **122'**; (3) frequency-division duplexing (FDD), with wide transmit signal bandwidth and a wide (e.g., >30 MHz) spacing between the transmit band and the receive band necessitating a high rate of transitions among levels and with rapid response of voltage  $v_y$  **122'**; and (4) FDD with low transmit bandwidth and a small separation (e.g., <<30 MHz) between the transmit and receive bands, necessitating lower rates of transition in voltage  $v_x$  **117'** and the need for significant removal of high-frequency content in  $v_y$  **122'** to reduce noise content in the receive band.

It is recognized, therefore, that some implementations of system **300** require many transitions in the voltage level of  $v_x$  **117'** such that  $v_y$  **122'** has fast response with minimal filtering of high-frequency content (e.g., rapid modulation of  $v_x$  **117'** with a high cutoff frequency of transition shaping filter **118'**), while other implementations of system **300** might require fewer voltage transitions of  $v_x$  **117'** but much more limited high frequency content such that  $v_y$  **122'** has slower response with more filtering of high-frequency content (e.g., slow modulation of  $v_x$  **117'** with a low cutoff frequency of transition shaping filter **118'**). Described embodiments achieve both high transition rate (e.g., fast response) and low transition rate (e.g., reduced high-frequency content) by employing modified transitioning techniques for changing the voltage level supplied to PA **108'**.

For example, for a fast transition between two levels with limited filtering of high-frequency content in  $v_y$  **122'**, voltage modulator **116'** might be used to step voltage  $v_x$  **117'** between the voltage levels  $V_1$ ,  $V_2$ ,  $V_3$ , etc., and transition shaping filter **118'** provides the necessary degree of filtering

9

in  $v_Y$  122'. To further reduce high frequency content, voltage modulator 116' might employ switching patterns in the voltage transitions to further shape the  $v_Y$  122' and reduce high frequency content. In situations where a fast response is required, filter 118' might be implemented with a relatively high cutoff frequency, such that when voltage  $v_X$  117' is modulated among voltage levels (e.g., switching from  $V_1$  to  $V_2$ , etc.),  $v_Y$  122' transitions quickly from  $V_1$  to  $V_2$ . When fewer total level changes are needed but reduced high-frequency content in  $v_Y$  122' is necessary, described embodiments employ multi-pulse voltage level transitions such as shown in FIG. 4.

FIGS. 4A, 4B and 4C are plots of illustrative switching patterns 402, 404 and 406 for transitions among levels that, for example, would be observed in voltage 117' as shown in FIG. 3 in response to operation of switches 116'. Single-pulse transition 402 of FIG. 4A represents a standard change among voltage levels. In described embodiments, double-pulse transition 404 of FIG. 4B enables improved shaping of the frequency content of the resulting output waveform, at the expense of higher switching loss for the transition. Higher numbers of pulses might also be employed in a transition of voltage level  $v_X$  117', for example, "triple-pulse" transition 406 of FIG. 4C, or more generally, an "N-pulse" transition, where N is an integer greater than 1.

A trade-off exists between the number of pulse transitions and switching energy dissipation of drain modulator 116'. Employing double-pulse transition 404 results in higher switching energy dissipated (per net level change) as compared with the switching energy dissipated for single-pulse transition 402. However, employing multiple pulse transitions (e.g., transitions 404 or 406) with appropriate timing and duration of the pulses results in reduced high-frequency content in  $v_Y$  122' as compared to a single-pulse transition. Higher-frequency content can be further reduced with higher-order numbers of pulses per transition such as the triple-pulse transition 406.

FIGS. 5A, 5B and 5C are series of plots of the AC components (e.g., without DC offset) of the voltage transitions shown in FIG. 4, plotted as voltage versus time. For example, the curves shown in FIGS. 5A-5C might be observed as the voltage  $v_X$  117' provided from drain modulator 116' to transition shaping filter 118'. Curve 502 in FIG. 5A illustrates the AC component of a double-pulse switching transition among levels that would be observed in voltage  $v_X$  117' as shown in FIG. 3.  $T_1$  and  $T_2$  represent the duration (or width) of each pulse in voltage  $v_X$  117', where  $T_D = T_1 + 0.5T_2$ . The double-pulse transition can be expressed as the sum of the voltage step  $v_S(t)$  shown as curve 504 in FIG. 5B and the voltage pulse  $v_P(t)$  shown as curve 506 in FIG. 5C.

FIG. 5A shows the AC component of a double-pulse voltage transition of  $v_X$  117' among voltage levels (e.g.,  $V_1$ ,  $V_2$ ,  $V_3$ , etc.). As will be shown, by proper sizing of the duration (e.g.,  $T_1$  and  $T_2$ ) and positioning (e.g., at what time,  $t$ , the pulses occur) of the pulse  $v_P$  (e.g., as shown in FIG. 5C) that is added to voltage  $v_S$  to form  $v_X$ , content in a frequency range of interest can be reduced in  $v_X$  117' and  $v_Y$  122'. For example, the Fourier transforms of the waveforms in FIG. 5 can be shown as:

$$v_X(\omega) = v_S(\omega) + v_P(\omega) = \frac{1}{\omega} e^{-j\pi/2} - \frac{2}{\omega} \sin\left(\frac{\omega T_2}{2}\right) e^{-j\omega T_D}$$

$$v_S(\omega) = \frac{1}{\omega} e^{-j\pi/2}$$

10

-continued

$$v_P(\omega) = -\frac{2}{\omega} \sin\left(\frac{\omega T_2}{2}\right) e^{-j\omega T_D}$$

where  $v_X$  is voltage waveform shown in FIG. 5A,  $v_S$  is the step waveform shown in FIG. 5B, and  $v_P$  is the pulse waveform shown in FIG. 5C. Thus, by properly selecting  $T_D$  and  $T_2$  (or  $T_1$  and  $T_2$ ), and properly timing them at time  $t$ , the amplitude of  $v_X$  in a frequency range of interest can be reduced.

Appropriate selection of  $T_1$  and  $T_2$  results in desirable filtering in a double-pulse transition. In one embodiment,  $T_1 = T_2$ , which places a null at an angular frequency given by:

$$\omega_x = \frac{\pi}{3T_2}$$

The selection  $T_1 = T_2$  enables easy digital implementation with operation on a fixed time grid. Thus, an AC component of the output voltage of the voltage modulator associated with a voltage transition is represented in the frequency domain by:

$$v_X(\omega) = v_S(\omega) + v_P(\omega) = \frac{1}{\omega} e^{-j\pi/2} - \frac{2}{\omega} \sin\left(\frac{\omega T_2}{2}\right) e^{-j\omega T_D}$$

where  $v_X(\omega)$  is a Fourier representation of a multi-pulse output voltage of the at least one voltage modulator,  $v_S(\omega)$  is a Fourier representation of a step function associated with a transition between discrete voltages of the at least one voltage modulator, and  $v_P(\omega)$  is a Fourier representation of a pulse function associated with a transition between discrete voltages of the at least one voltage modulator, and where  $T_2$  and  $T_D$  are time durations associated with the pulse function. Other embodiments might employ other relationships between  $T_1$  and  $T_2$  to shape the frequency content of  $v_X$ , as shown in FIGS. 7 and 8, discussed below.

FIGS. 6A-6C show plots of the frequency-domain voltage magnitude content for the corresponding voltage transition patterns shown in FIGS. 5A-5C. For example, the curves shown in FIGS. 6A-6C might be observed as spectral components of the voltage 117' provided from drain modulator 116' to transition shaping filter 118'. FIG. 6A shows the complete spectral content (of the ac component) while FIGS. 6B and 6C show constituent parts of that spectral content associated with the component waveform of FIG. 5A shown in FIGS. 5B and 5C. As shown in FIG. 6A, using the double-pulse transition enables a null (or small-amplitude region) to be placed in the frequency domain content of voltage 117', allowing improved filtering by filter 118' of frequency-domain components in voltage 122' provided to PA 108'.

Referring now to FIG. 6A, curve 602 illustrates the frequency response of a double pulse voltage transition. As shown, a double pulse transition has content at higher frequencies (e.g., above  $\omega=1$ ) that is larger than that of just a step (e.g., curve 604 of FIG. 6B). Curve 606 in FIG. 6C illustrates the frequency response of example pulse  $v_P$  shown in FIG. 5C representing the difference between the double-pulse transition and the single-pulse transition, which also has significant higher frequency content (e.g., near  $\omega=1$  and above). However, by selecting an appropriate pulse width and delay and adding it to the single-pulse

transition, as shown by curve 602 in FIG. 6A, the double-pulse transition has greatly reduced frequency content in a range of interest (e.g., the null located at  $\omega=1$ ). This reduced frequency content lowers the burden on transition filter 118' in this frequency range, enabling the use of a transition filter with a higher cutoff frequency than with only a single pulse transition. Although the very-high-frequency content of  $v_X$  117' for the double-pulse transition (e.g., well above  $\omega=1$ , such as  $\omega\sim 2-3$ ) is actually higher than that of the single-pulse transition, content in this frequency range is much more readily filtered by transition filter 118'.

FIGS. 7A and 7B show plots of illustrative double-pulse transitions of voltage 117', including both AC and DC components. Curve 702 in FIG. 7A illustrates the time-domain response of a drain modulation waveform having double-pulse transitions on voltage  $V_X$  117' before filter 118', with  $T_1=T_2=5$  ns. Curve 704 in FIG. 7B illustrates the power spectral density of a single-pulse transition and curve 708 illustrates the power spectral density of a double-pulse transition (e.g., at voltage 117' before filter 118'). Curve 710 illustrates the power spectral density of the slew-rate limited waveform output from filter 118' (e.g., voltage 122' after filter 118') for a double-pulse transition.

FIG. 8 shows a similar plot as FIG. 7B, for double-pulse transitions having  $T_1=4$  ns and  $T_2=3.5$  ns. Curve 802 illustrates the power spectral density of a single-pulse transition and curve 804 illustrates the power spectral density of a double-pulse transition (e.g., at voltage 117' before filter 118'). Curve 810 illustrates the power spectral density of the slew-rate limited waveform output from filter 118' with a double-pulse transition. As illustrated by curve 804, the notch (e.g., notch 806) in the power spectral density owing to the double transition with these times is shallower and wider than in the case of the notch (e.g., notch 706) shown in FIG. 7B.

Thus, as shown in FIGS. 7B and 8, as compared to employing a single-pulse transition (e.g., as illustrated by curves 704 and 802), employing a double-pulse transition (e.g., as illustrated by curves 708 and 804) results in a reduction in amplitude of spectral components in a frequency range of interest (e.g., in this illustrative embodiment, between 30 and 40 MHz, as indicated by notches 706 and 806). It should be noted, however, that such a reduction in amplitude might be provided at any desired frequency or frequency range by using multiple pulse transitions. It should also be noted that employing additional pulses (e.g., more than a single pulse) increases high frequency spectral content due to the additional transition edges (e.g., the amplitude of spectral content of curve 708 is greater spectral than the amplitude of the spectral content of curve 704 above approximately 60 MHz, and the amplitude of the spectral content of curve 804 is greater than the amplitude of the spectral content of curve 802 above approximately 70 MHz). However, this high frequency spectral content can more easily be filtered by a single filter (e.g., transition shaping filter 118), as indicated by curves 710 and 810. Thus, transition shaping filter 118 can be used to control, shape or attenuate the amplitude of spectral components resultant from the multiple pulse transitions. Accordingly, as illustrated in FIGS. 7B and 8, employing a double-pulse transition (e.g., curves 708 and 804) in combination with the transition shaping filter having appropriately selected filter characteristics results in a reduction of spectral component amplitude in a desired frequency range.

Referring now to FIG. 9, multilevel power amplifier system 900 includes drain modulator 116" and a reconfigurable transition shaping filter 118" supplying an RF amplifier

108". Similar to the system shown in FIG. 3, drain modulator 116" modulates the voltage applied to PA 108" by switching voltages among multiple discrete voltage levels, shown as voltages  $V_1$ ,  $V_2$ , and  $V_3$ , to provide output voltage 117". Transition shaping filter 118" shapes (e.g., smooths) transitions of output voltage 117" such that voltage  $v_Y$  provided as bias signal 122" to PA 108" has smooth transitions with high-frequency content removed. As shown, some embodiments of drain modulator 116" include as many switches (e.g., switches  $S_1$ ,  $S_2$  and  $S_3$ ) as there are input voltages (e.g.,  $V_1$ ,  $V_2$ , and  $V_3$ ). Drain modulator 116" employs each of the switches to select a corresponding discrete input voltage level to provide as bias signal 122" to PA 108".

Employing a dynamically reconfigurable transition shaping filter 118" allows described embodiments to be employed over wide operating ranges, and applied separately from or together with multi-pulse transitions such as shown in FIG. 4. By switching in and out filter components using switches  $S_{X1}$ ,  $S_{X2}$ ,  $S_Y$  and  $S_Z$ , the bandwidth of filter 118" can be adjusted in response to varying operating conditions (e.g., TDD vs. FDD operation, operation with different transmit and receive band separations, operation in different modes such as envelope tracking, envelope tracking advanced, adaptive power tracking, etc.).

It will be recognized that many other reconfigurable filter designs are possible. This includes use of switches to add or remove filter components and/or stages (e.g., change filter cutoff and/or order) and/or use of other numbers and locations of switches  $S_{X1}$ ,  $S_{X2}$ ,  $S_Y$  and  $S_Z$ . Although use of shunt switches (especially ground-referenced shunt switches such as switch  $S_Z$ ) is easily implemented and operated, other switch configurations are possible. In addition to switches in series and/or parallel with filter elements, more sophisticated structures might be employed. For example, to bridge or short a series component, a "T" structure (e.g., switches  $S_{X1}$ ,  $S_{X2}$ , and  $S_Y$ ) might be beneficially employed since parasitic capacitance across switches  $S_{X1}$  and  $S_{X2}$  do not bypass the filter inductor  $L_1$  when switches  $S_{X1}$ ,  $S_{X2}$  and  $S_Y$  are closed, but rather are shunted to ground. Thus, the "T" shown in FIG. 9 reduces the impact of switch capacitance on performance of filter 118".

Thus, the characteristics of filter 118" might be changed by reconfiguring switches  $S_{X1}$ ,  $S_{X2}$ ,  $S_Y$  and  $S_Z$  or by adjusting the values of configurable components (e.g., if one or more of  $L_1$ ,  $L_2$ ,  $L_3$ ,  $R_3$ ,  $C_1$  and  $C_2$  are variable components).

Although FIG. 9 is shown as employing only switches and passive components, active components might additionally or alternatively be employed. For example, reconfigurable filters might include electrically variable filter components such as varactors, crossed-field reactors or similar components, transistors, operational amplifiers and other components that allow electronic adjustment of filter performance. Some embodiments might employ multiport filter components. For example, a two-winding, two-port magnetic structure (e.g., a coupled inductor or transformer) might have a first port used as a filter inductor, and a second port shunted by a switch, such that the effective inductance of the first port depends upon the state of the configuration switch. Filter performance might also be adjusted by actively adjusting filter damping.

Transition shaping filter 118" includes one or more filter stages comprising passive components. Transition shaping filter 118" includes a first filter stage including passive components  $L_1$ ,  $L_3$ ,  $R_3$  and  $C_1$  and switches  $S_{X1}$ ,  $S_{X2}$ ,  $S_Y$  and  $S_Z$ . Further, the embodiment shown in FIG. 9 also includes a second filter stage that also includes passive components



$L_2$  and  $C_2$ . Inclusion of switches  $S_{X1}$ ,  $S_{X2}$ ,  $S_Y$  and  $S_Z$  enables filter **118** to be dynamically configured during operation of system **100**. For example, a first filter configuration is provided when switches  $S_Y$  and  $S_Z$  are closed and switches  $S_{X1}$  and  $S_{X2}$  are open. A second configuration of the filter is provided when switch  $S_Y$  is closed and switches  $S_{X1}$ ,  $S_{X2}$  and  $S_Z$  are open. A third configuration of the filter is provided when switches  $S_{X1}$  and  $S_{X2}$  are closed and switches  $S_Y$  and  $S_Z$  are open. Each of these configurations provides a different combination of high-frequency attenuation filter characteristics and response speed of voltage **122** provided to PA **108**.

Referring now to FIG. **10**, multilevel power amplifier system **1000** includes multiple drain voltage modulators and a multiple-input, single-output transition filter. As shown in FIG. **10**, inductor  $L_{2,4}$  is coupled to voltage modulator **116B**, and inductor  $L_2$  is coupled to voltage modulator **116A**. Inductor  $L_{2,4}$  might have an inductance value that is equal to, less than, or greater than the inductance of  $L_2$ . If the inductance of  $L_2$  is much larger than the inductance of  $L_{2,4}$ , then there will be a slower response of voltage  $V_Y$  to inputs from modulator **116A** than from modulator **116B** if only one of the modulators are employed at a given time. Thus, under operating conditions of system **100** where low ripple/noise and low bandwidth are desired, power can be provided to PA **108** from modulator **116A**, with all the switches of modulator **116B** remaining in the off or open position. Under operating conditions of system **100** where higher response speed is desired, power can be provided to PA **108** from modulator **116B**, with all the switches of modulator **116A** remaining in the off or open position.

Under operating conditions of system **1000** where a highest response speed is desired, power can be provided to PA **108** from both modulator **116A** and modulator **116B** (e.g., modulator **116A** and modulator **116B** are operated in parallel with synchronized timing among the corresponding switches  $S_1$ ,  $S_2$ ,  $S_3$ ,  $S_{1,4}$ ,  $S_{2,4}$ , and  $S_{3,4}$ ). Use of both modulator **116A** and modulator **116B** in parallel also provides the opportunity to source high power at low loss. Use of both modulator **116A** and modulator **116B** in parallel further allows described embodiments to shape the transitions in voltage  $V_Y$  by staggering the timing with which the switching transitions are made in modulator **116A** and modulator **116B** (e.g., a configurable timing delay or offset between the switching among levels in one voltage modulator in reference to the switching of the other voltage modulator).

Described embodiments might provide magnetic coupling between inductors  $L_2$  and  $L_{2,4}$  shown in FIG. **10**. Magnetic coupling of inductors  $L_2$  and  $L_{2,4}$  allows shaping differential-mode currents to output **122** from voltage modulators **116A** and **116B** separately from shaping common-mode currents from each of the modulators **116A** and **116B** to output **122**. Further, such magnetic coupling might reduce the size of inductors  $L_2$  and  $L_{2,4}$ . In some embodiments,  $L_2$  and  $L_{2,4}$  might employ a common core structure, without magnetic coupling, which still might result in a reduction in the size of inductors  $L_2$  and  $L_{2,4}$ . Although shown in FIG. **10** as employing two voltage modulators **116A** and **116B**,  $M$  modulators, where  $M$  is an integer greater than one, can be utilized with a variety of kinds of multi-input (e.g.,  $M$  ports, such that there is one port for each modulator) systems having at-least-one-output to one or more corresponding PAs **108**. As described, the  $M$  modulators might be utilized individually (with the other modulator "off") or together in

a coordinated fashion to provide various characteristics in the output waveform and its transitions to one or more PAs **108** coupled to the filter.

FIG. **11** is a flow diagram of a voltage transition technique **1100** that might be employed by system **100** shown in FIG. **1**, for example. At block **1102**, operation of system **100** starts, for example by powering system **100**. At block **1104**, one or more operating conditions of system **100** are determined. For example, whether system **100** is operating in one of 4 modes: (1) adaptive power tracking (APT) mode, in which the drain voltage is adapted slowly (e.g., by adjusting one or more of  $V_1$ ,  $V_2$ , and  $V_3$ , and/or by switching among them at a low rate); (2) time-division duplexing (TDD) mode, in which the signal bandwidth is wide and there is a high rate of transitions among levels with rapid response of voltage  $V_Y$ ; (3) frequency-division duplexing (FDD), with wide transmit signal bandwidth and a wide (e.g., >30 MHz) spacing between the transmit band and the receive band necessitating a high rate of transitions among levels and rapid response of voltage  $V_Y$ ; and (4) FDD with low transmit bandwidth and a small separation (e.g., <<30 MHz) between the transmit and receive bands, necessitating lower rates of transition in voltage  $V_x$  and the need for significant removal of high-frequency content in  $V_Y$  to reduce noise content in the receive band.

At block **1106**, it is determined whether the operating conditions of system **100** require fast transitions in voltage **122**, or high filtering capability of voltage **122**. Although shown as two decision paths (e.g., "Fast Transitions" and "High Filtering"), there might be additional decision paths. For example, one decision path for each mode of operation described above. Other numbers of decision paths might be beneficially employed. If, at block **1106**, a decision is made that fast voltage transitions are required, then at block **1108** components are removed from transition shaping filter **118** (e.g., via switching one or more of switches  $S_{X1}$ ,  $S_{X2}$ ,  $S_Y$  and  $S_Z$  of FIG. **9**).

At block **1110**, voltage modulator **116** is set to transition between voltages using fewer transition pulses (e.g., the single pulse transition shown in FIGS. **4** and **5** versus a double-, triple- or  $N$ -pulse transition signal). At block **1116**, voltage **122** is determined and supplied to PA **108**.

Alternatively, if, at block **1106**, a decision is made that high noise filtering is required, then process **1100** proceeds to block **1112** where components are added into transition shaping filter **118** (e.g., via switching one or more of switches  $S_{X1}$ ,  $S_{X2}$ ,  $S_Y$  and  $S_Z$  of FIG. **9**). Process **1100** proceeds to block **1114**, where voltage modulator **116** is set to transition between voltages using additional transition pulses (e.g., the double-, triple- or  $N$ -pulse transition signal instead of the single pulse transition as shown in FIGS. **4** and **5**). In embodiments where more operating modes are desired, additional decision branches/blocks might be provided having modes that combine high-cutoff and fast response filter configurations with additional transition pulses, and low cutoff/slow response filter configurations with fewer transition pulses. In embodiments having multiple PAs **108** and/or multiple voltage modulators **116**, blocks **1106** through **1114** might be repeated for each PA **108**.

At block **1118**, system **100** is operated in accordance with the operating conditions determined at block **1104** and the settings adapted in blocks **1106** through **1114**. During operation at block **1118**, voltage level of voltage **122** is modulated and supplied to PA **108**, for example by switching one or more of switches  $S_1$ ,  $S_2$ , and  $S_3$ . At block **1120**, if settings of system **100** need to change, for example if operating

15

conditions of system 100 change, then processing returns to block 1104 and adjustments in settings to system 100 can be determined and applied. Otherwise, system 100 continues to operate with its current settings at block 1118.

It should be appreciated that typically the operating voltage is set repeatedly (and typically very rapidly) in response to the characteristics of the RF signal to amplify and transmit. Thus, the operating voltage typically changes at a rate that is much faster than a rate at which transition shaping filter is reconfigured. It is, however, possible that in some applications the rate at which the transition filter is reconfigured is equal to or greater than the rate at which the operating voltage is set.

It should also be appreciated that the switches (e.g., switches  $S_1$ ,  $S_2$ ,  $S_3$ ,  $S_{1,A}$ ,  $S_{2,A}$ ,  $S_{3,A}$ ,  $S_{X1}$ ,  $S_{X2}$ ,  $S_Y$  and  $S_Z$ ) might be provided as mechanical switches or might preferably be implemented as one or more transistors or other semiconductor switching elements. Further, although shown as single devices for illustrative purposes, described embodiments might employ multiple semiconductor switches coupled together to achieve desired electrical characteristics from the combination, such as a desired physical size (e.g., gate width and length) or operating characteristic (e.g., isolation, voltage blocking capability, switching speed, threshold voltage, gain, bidirectionality, etc.).

Thus, as described herein, embodiments provide a radio frequency (RF) amplifier system having at least one amplifier. The at least one amplifier includes an RF input port, an RF output port and a drain bias port. At least one voltage modulator is coupled to the bias port of the least one amplifier to provide a bias voltage. The bias voltage is selected by switching among a plurality of discrete voltages. At least one filter circuit is coupled between the at least one voltage modulator and the at least one amplifier. The at least one filter circuit controls spectral components resultant from transitions in the bias voltage when switching among the plurality of discrete voltages. Hence, the bias signal provided to the amplifier, is provided having the amplitudes of undesirable spectral components resultant from the transitions attenuated (and ideally, eliminated). A controller dynamically adapts at least one setting of the at least one voltage modulator by using multi-pulse transitions when switching among the plurality of discrete voltages for a first operating condition of the RF amplifier.

Reference herein to “one embodiment” or “an embodiment” means that a particular feature, structure, or characteristic described in connection with the embodiment can be included in at least one embodiment of the claimed subject matter. The appearances of the phrase “in one embodiment” in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments necessarily mutually exclusive of other embodiments. The same applies to the term “implementation.”

As used in this application, the words “exemplary” and “illustrative” are used herein to mean serving as an example, instance, or illustration. Any aspect or design described herein as “exemplary” or “illustrative” is not necessarily to be construed as preferred or advantageous over other aspects or designs. Rather, use of the words “exemplary” and “illustrative” is intended to present concepts in a concrete fashion.

Additionally, the term “or” is intended to mean an inclusive “or” rather than an exclusive “or”. That is, unless specified otherwise, or clear from context, “X employs A or B” is intended to mean any of the natural inclusive permutations. That is, if X employs A; X employs B; or X employs

16

both A and B, then “X employs A or B” is satisfied under any of the foregoing instances. In addition, the articles “a” and “an” as used in this application and the appended claims should generally be construed to mean “one or more” unless specified otherwise or clear from context to be directed to a singular form.

To the extent directional terms are used in the specification and claims (e.g., upper, lower, parallel, perpendicular, etc.), these terms are merely intended to assist in describing the embodiments and are not intended to limit the claims in any way. Such terms, do not require exactness (e.g., exact perpendicularity or exact parallelism, etc.), but instead it is intended that normal tolerances and ranges apply. Similarly, unless explicitly stated otherwise, each numerical value and range should be interpreted as being approximate as if the word “about”, “substantially” or “approximately” preceded the value of the value or range.

Signals and corresponding nodes or ports may be referred to by the same name and are interchangeable for purposes here.

Moreover, the terms “system,” “component,” “module,” “interface,” “model” or the like are generally intended to refer to a computer-related entity, either hardware, a combination of hardware and software, software, or software in execution. For example, a component may be, but is not limited to being, a process running on a processor, a processor, an object, an executable, a thread of execution, a program, and/or a computer. By way of illustration, both an application running on a controller and the controller can be a component. One or more components may reside within a process and/or thread of execution and a component may be localized on one computer and/or distributed between two or more computers.

Some embodiments might be implemented in the form of methods and apparatuses for practicing those methods. Described embodiments might also be implemented in the form of program code embodied in tangible media, such as magnetic recording media, hard drives, floppy diskettes, magnetic tape media, optical recording media, compact discs (CDs), digital versatile discs (DVDs), solid state memory, hybrid magnetic and solid state memory, or any other machine-readable storage medium, wherein, when the program code is loaded into and executed by a machine, such as a computer, the machine becomes an apparatus for practicing the claimed invention. Described embodiments might also be implemented in the form of program code, for example, whether stored in a storage medium, loaded into and/or executed by a machine, or transmitted over some transmission medium or carrier, such as over electrical wiring or cabling, through fiber optics, or via electromagnetic radiation, wherein, when the program code is loaded into and executed by a machine, such as a computer, the machine becomes an apparatus for practicing the claimed invention. When implemented on a processing device, the program code segments combine with the processor to provide a unique device that operates analogously to specific logic circuits. Such processing devices might include, for example, a general purpose microprocessor, a digital signal processor (DSP), a reduced instruction set computer (RISC), a complex instruction set computer (CISC), an application specific integrated circuit (ASIC), a field programmable gate array (FPGA), a programmable logic array (PLA), a microcontroller, an embedded controller, a multi-core processor, and/or others, including combinations of the above. Described embodiments might also be implemented in the form of a bitstream or other sequence of signal values electrically or optically transmitted through a medium,

17

stored magnetic-field variations in a magnetic recording medium, etc., generated using a method and/or an apparatus as recited in the claims.

It should be understood that the steps of the methods set forth herein are not necessarily required to be performed in the order described, and the order of the steps of such methods should be understood to be merely illustrative. Likewise, additional steps may be included in such methods, and certain steps may be omitted or combined, in methods consistent with various embodiments.

It will be further understood that various changes in the details, materials, and arrangements of the parts that have been described and illustrated herein might be made by those skilled in the art without departing from the scope of the following claims.

We claim:

1. A radio frequency (RF) amplifier system comprising:
  - at least one amplifier having an RF input port, an RF output port and a bias port;
  - at least one voltage modulator coupled to the bias port of the at least one amplifier to provide a bias voltage, the bias voltage selected by switching among a plurality of discrete voltages;
  - at least one filter circuit coupled between the at least one voltage modulator and the at least one amplifier, the at least one filter circuit configured to control at least some spectral components resultant from transitions in the bias voltage when switching among the plurality of discrete voltages; and
  - a controller configured to dynamically adapt at least one setting of the at least one voltage modulator by using multi-pulse transitions when switching among the plurality of discrete voltages in a first operating condition of the RF amplifier, wherein the controller is configured to adapt at least one setting of the at least one voltage modulator to select the bias voltage among the discrete voltages by the at least one voltage modulator according to a switching pattern having two or more transition pulses.
2. The system of claim 1 wherein the multi-pulse transitions are selected to reduce spectral components at the RF output port of the at least one amplifier.
3. The system of claim 2, wherein the spectral components result from switching among the plurality of discrete voltages.
4. The system of claim 1, wherein the controller is further configured to dynamically adapt the at least one setting of the at least one voltage modulator by using single-pulse transitions when switching among the plurality of discrete voltages in a second operating condition of the RF amplifier.
5. The system of claim 4, wherein the transceiver is operable in one or more frequency bands and the controller is configured to adapt the at least one setting of the at least one voltage modulator and the at least one setting of the at least one filter circuit based, at least in part, on a frequency band in which the transceiver is operating.
6. The system of claim 1 wherein said at least one filter circuit is a reconfigurable circuit, wherein the controller is configured to adapt a configuration of the at least one filter circuit.
7. The system of claim 6, wherein the reconfigurable circuit comprises one or more configurable components, the controller configured to add or remove each of the one or more configurable components from the filter based on the operating mode of the RF amplifier.

18

8. The system of claim 1, wherein a number, duration and timing of the two or more transition pulses is selected based upon an operating mode of the RF power amplifier.

9. The system of claim 1, wherein the switching pattern is configured to reduce the spectral components in the bias voltage in a frequency range of interest when switching among the plurality of discrete voltages.

10. The system of claim 9, wherein the frequency range of interest corresponds to a receive band of the RF amplifier system.

11. The system of claim 9, wherein the switching pattern comprises:

- a first transition from a first discrete voltage level to a second discrete voltage level;
- a second transition from the second discrete voltage level to the first discrete voltage level; and
- a third transition from the first discrete voltage level to the second discrete voltage level.

12. The system of claim 11, wherein:

- a duration between the first transition and the second transition has a time,  $T_1$ ;
- a duration between the second transition and the third transition has a time,  $T_2$ ; and
- times  $T_1$  and  $T_2$  are selected to reduce spectral components in the frequency range of interest resulting from switching among the plurality of discrete voltages.

13. The system of claim 1, wherein the RF amplifier is used in a transceiver operable in at least two different modes, wherein the controller is configured to adapt at least one setting of the at least one voltage modulator by using multi-pulse transitions when switching among the plurality of discrete voltages based, at least in part, on the mode in which the transceiver is operating.

14. The system of claim 13, wherein the at least one filter circuit comprises a reconfigurable circuit, wherein the controller is configured to adapt a configuration of the at least one filter circuit based, at least in part, on the mode in which the transceiver is operating.

15. A method of operating a radio frequency (RF) amplifier comprising at least one controller, at least one amplifier, at least one voltage modulator, and at least one filter, the method comprising:

- determining, by the at least one controller, one or more operating characteristics of the RF amplifier;
- switching, by the voltage modulator in response to the determining, a bias voltage of the at least one amplifier among a plurality of discrete voltages by using multi-pulse transitions, wherein the multi-pulse transitions reduce spectral components at an RF output port of the at least one amplifier, the spectral components resulting from switching among the plurality of discrete voltages.

16. The method of claim 15, further comprising:

- controlling, via the multi-pulse transitions, spectral components resultant from transitions in the bias voltage when switching among the plurality of discrete voltages.

17. The method of claim 16 wherein controlling the spectral components comprises selecting the characteristics of the pulses in the multi-pulse transitions to reduce the amplitude of spectral components resultant from transitions in the bias voltage when switching among the plurality of discrete voltages in at least a predetermined frequency range.

19

18. The method of claim 15, further comprising:  
 using single-pulse transitions when switching among the  
 plurality of discrete voltages in response to the deter-  
 mined operating characteristics of the RF amplifier.

19. The method of claim 15, further comprising:  
 5 adapting, by the at least one controller, at least one setting  
 of the at least one voltage modulator to transition the  
 bias voltage among the discrete voltages by the at least  
 one voltage modulator according to a switching pattern  
 10 having two or more transition pulses, wherein a number,  
 duration and timing of the one or more transition  
 pulses is selected based on an operating mode of the RF  
 power amplifier, and wherein the switching pattern is  
 15 configured to reduce the spectral components in the  
 bias voltage in a frequency range of interest when  
 switching among the plurality of discrete voltages.

20. The method of claim 15, further comprising:  
 dynamically adapting, by the controller in response to the  
 determined operating characteristics, a configuration of  
 the at least one filter circuit, wherein the at least one  
 20 filter circuit comprises a reconfigurable circuit.

21. A radio frequency (RF) amplifier system comprising:  
 at least one amplifier having an RF input port, an RF  
 output port and a drain bias port;

at least one voltage modulator coupled to the bias port of  
 25 the least one amplifier, each of the at least one voltage  
 modulators operable to provide a selected bias voltage,  
 the bias voltage selected by switching among a plural-  
 ity of discrete voltages; and

a controller configured to dynamically adapt at least one  
 30 setting of the at least one voltage modulator by using  
 multi-pulse transitions when switching among the plu-

20

rality of discrete voltages to provide the selected bias  
 voltage in a first operating condition of the RF ampli-  
 fier, wherein multi-pulse transitions reduce spectral  
 components at the RF output port of the at least one  
 amplifier, the spectral components resulting from  
 switching among the plurality of discrete voltages.

22. The system of claim 21 further comprising at least one  
 filter circuit coupled between the at least one voltage modu-  
 lator and the at least one amplifier, the at least one filter  
 circuit configured to control transitions in the bias voltage  
 10 when switching among the plurality of discrete voltages.

23. The system of claim 21, wherein the controller is  
 further configured to dynamically adapt the at least one  
 setting of the at least one voltage modulator by using  
 15 single-pulse transitions when switching among the plurality  
 of discrete voltages in a second operating condition of the  
 RF amplifier.

24. The system of claim 21 wherein said at least one filter  
 circuit is a reconfigurable circuit, wherein the controller is  
 20 configured to adapt a configuration of the at least one filter  
 circuit.

25. The system of claim 21, wherein the controller is  
 configured to adapt at least one setting of the at least one  
 voltage modulator to transition the bias voltage among the  
 discrete voltages by the at least one voltage modulator  
 according to a switching pattern having two or more tran-  
 sition pulses, wherein a number, duration and timing of the  
 one or more transition pulses is selected based on the  
 operating mode of the RF power amplifier, and wherein the  
 30 switching pattern is configured to reduce spectral compo-  
 nents in the bias voltage.

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