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(54) **APPARATUS, SYSTEM, AND METHOD FOR  
DIGITAL MODULATION OF POWER  
AMPLIFIER IN POLAR TRANSMITTER**

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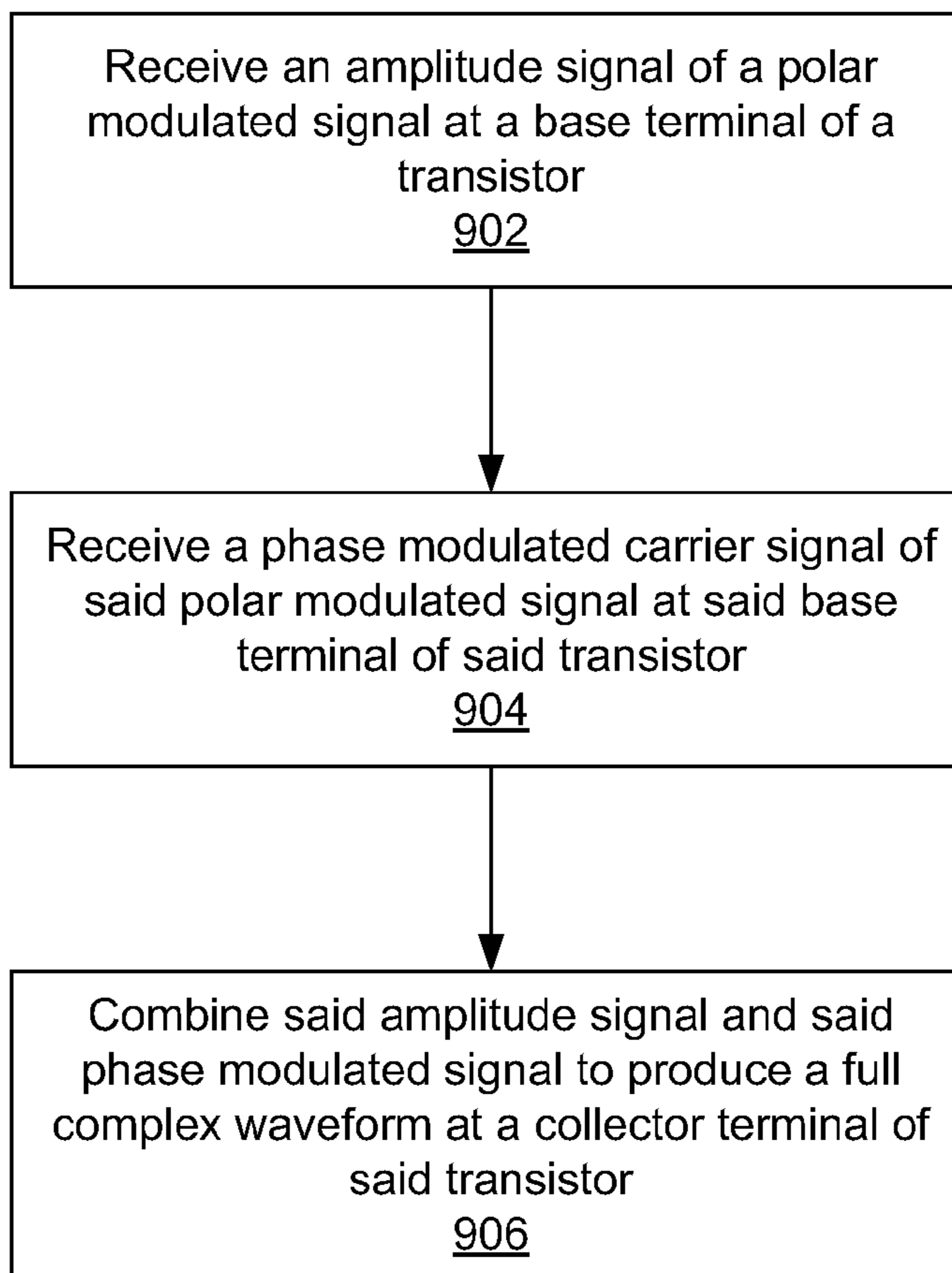
(57) **ABSTRACT**

An amplifier receives an amplitude signal of a polar modulated signal at a base or gate terminal of a transistor and receives a phase modulated carrier signal of the polar modulated signal at the base or gate terminal of the transistor. The amplifier combines the amplitude signal and the phase modulated signal to produce a full complex waveform at a collector or drain terminal of the transistor.

(21) Appl. No.: **11/696,204**

(22) Filed: **Apr. 4, 2007**

**900**



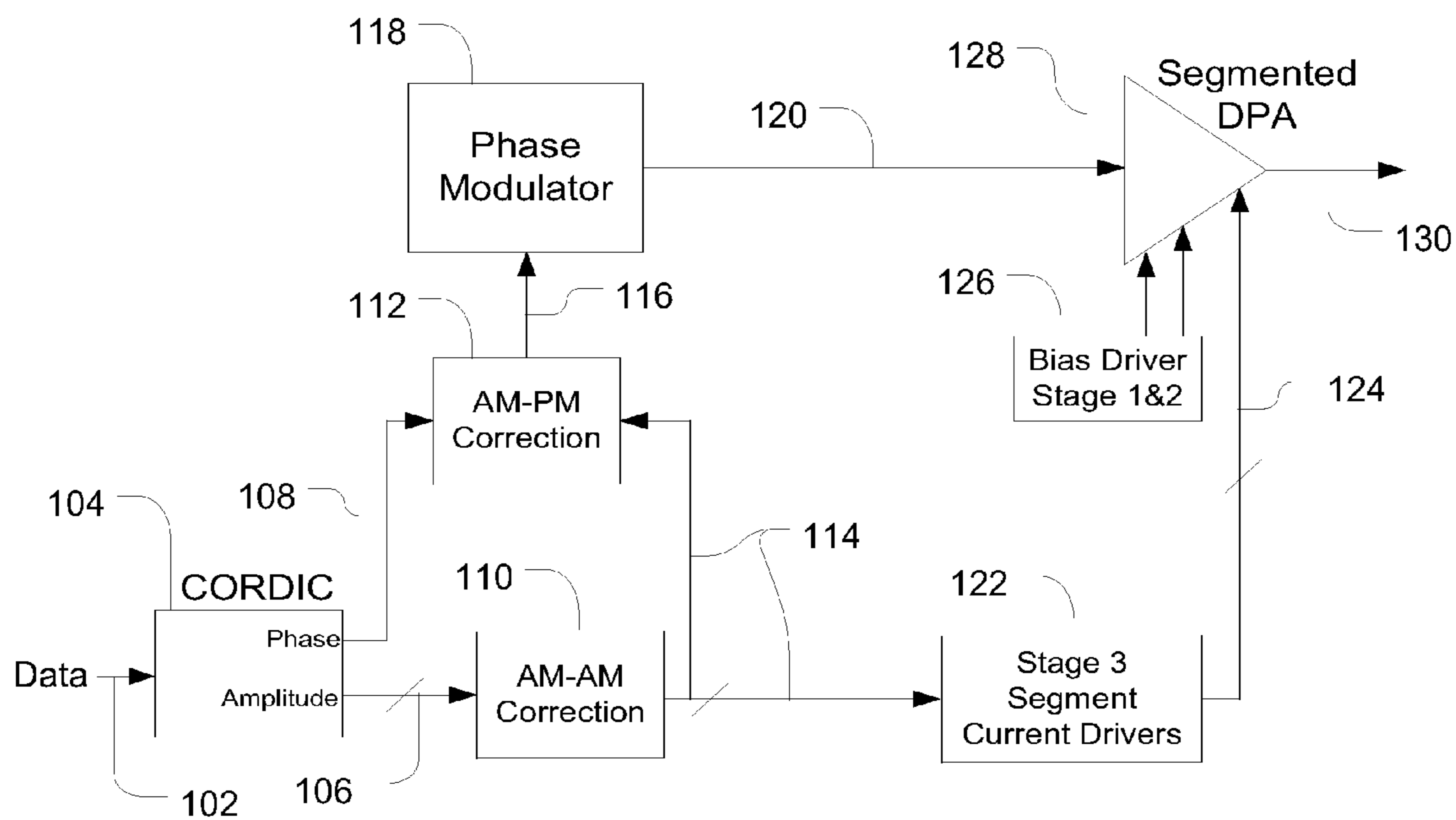


FIG. 1

200

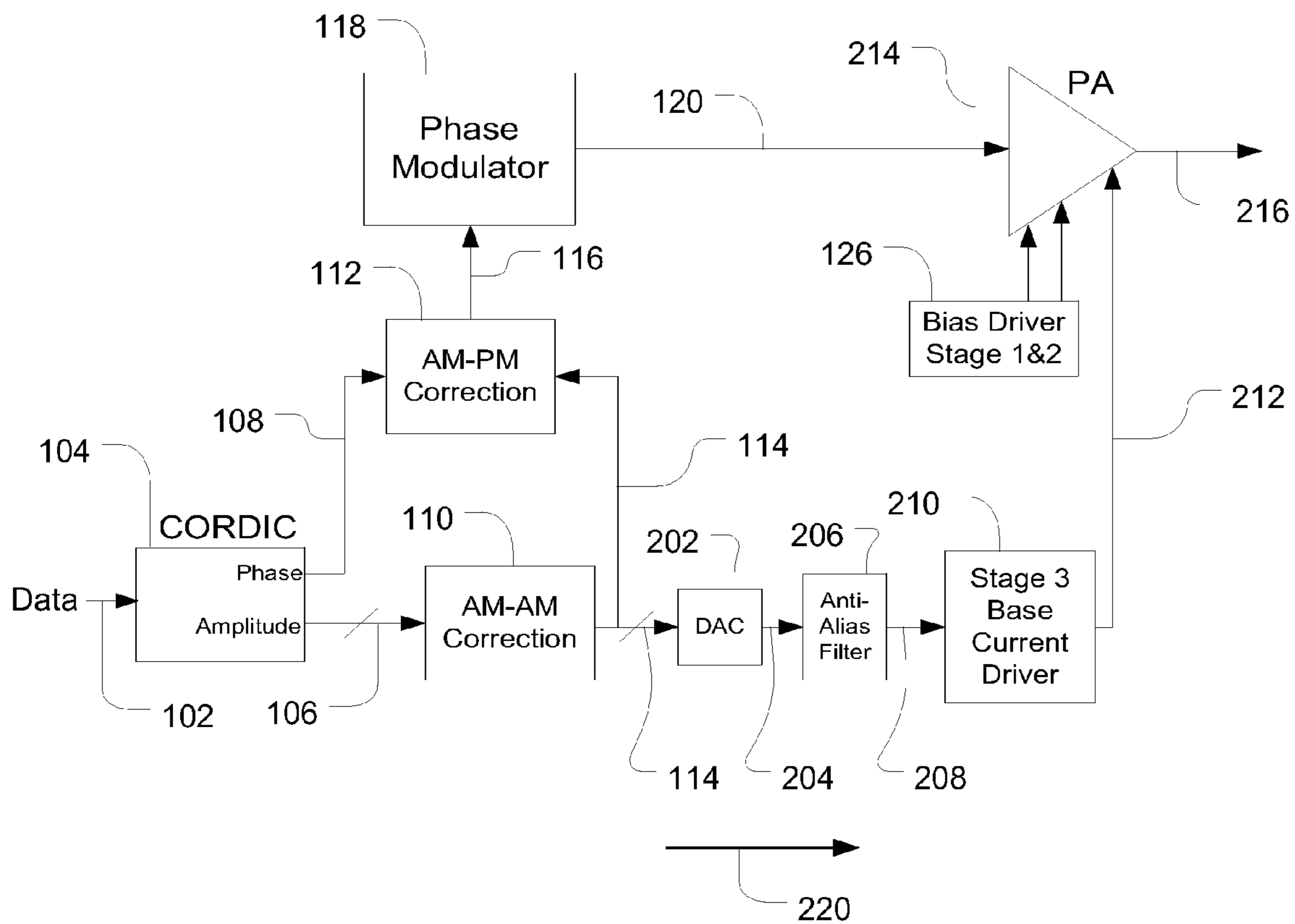


FIG. 2

300

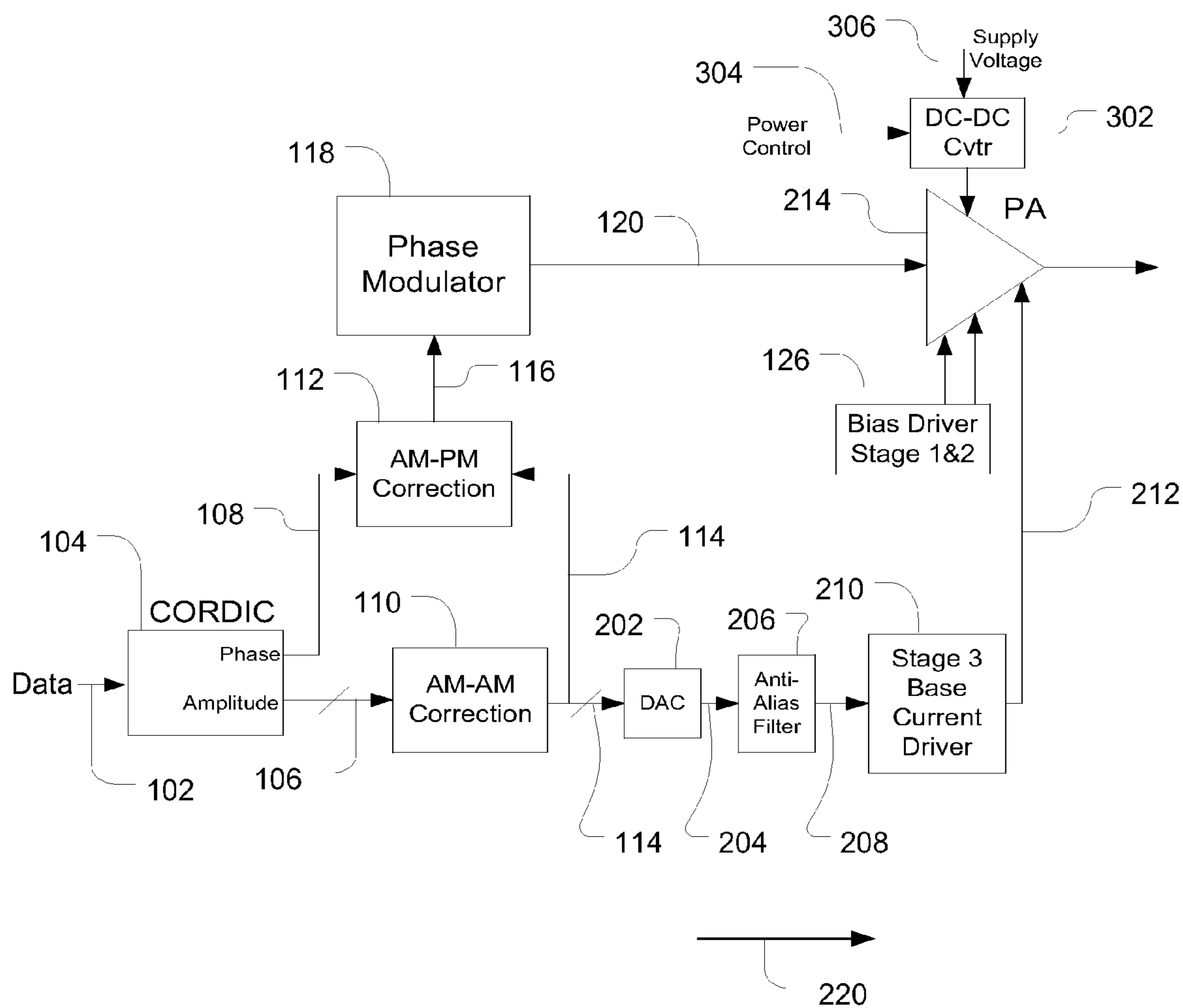


FIG. 3

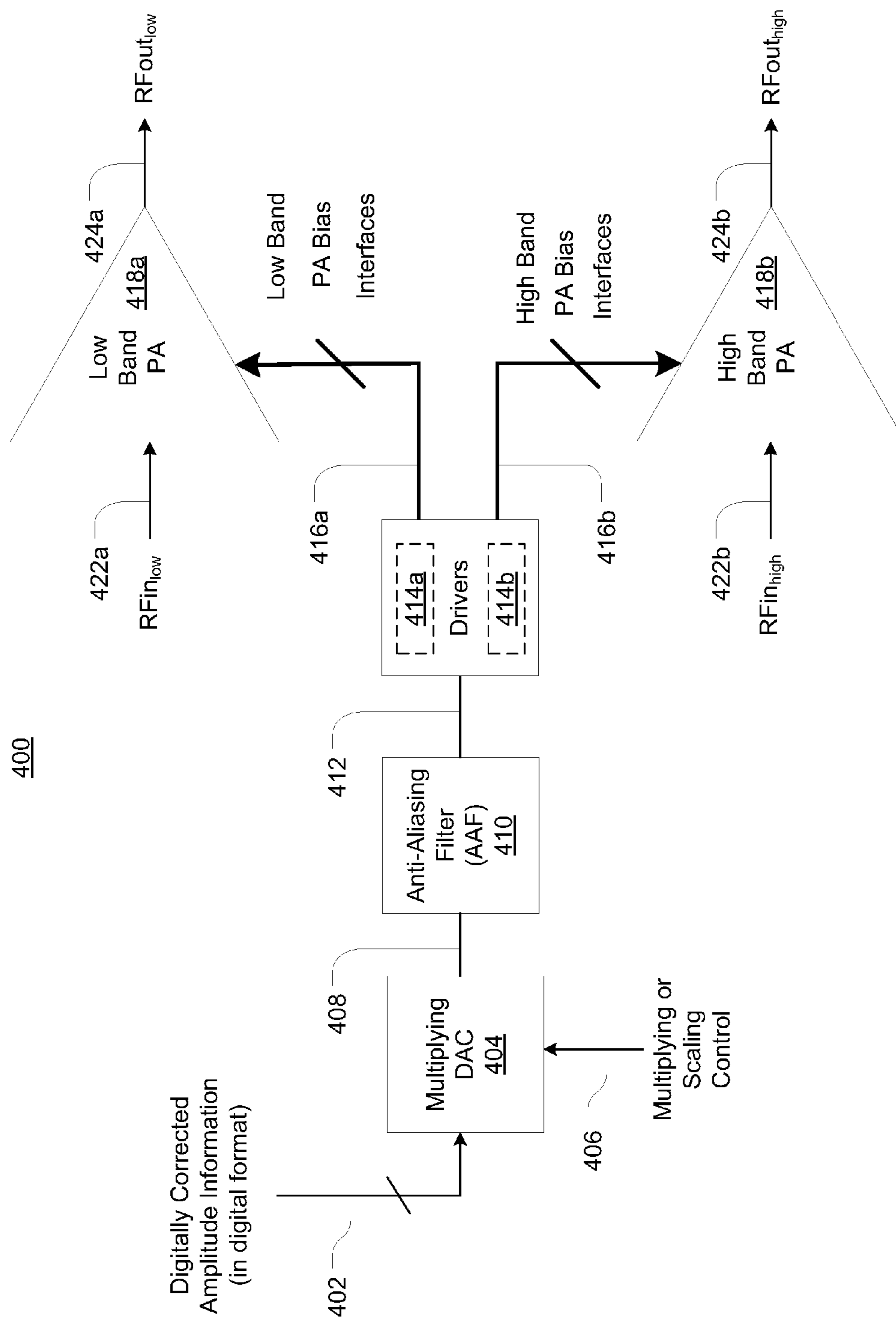


FIG. 4

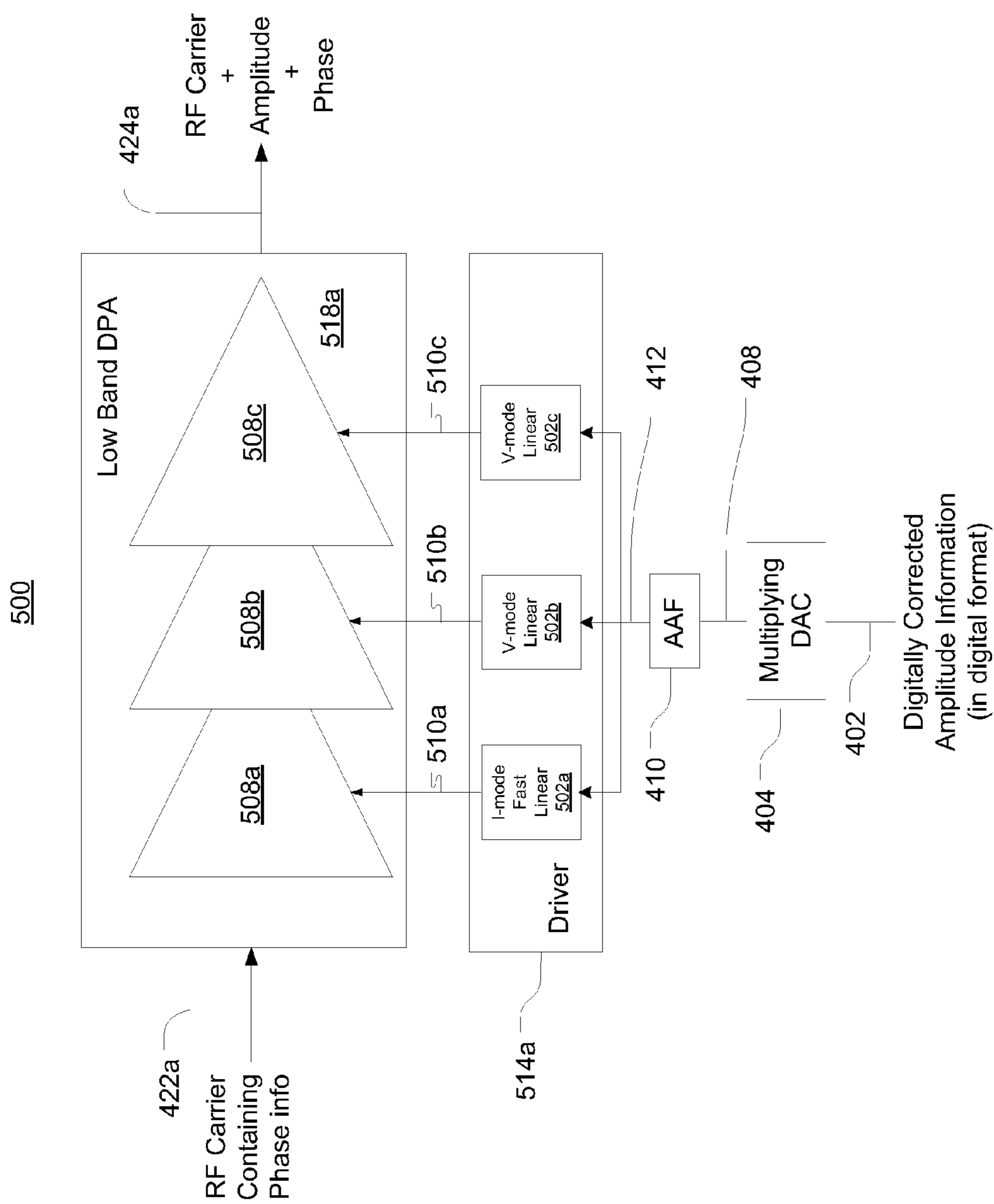


FIG. 5

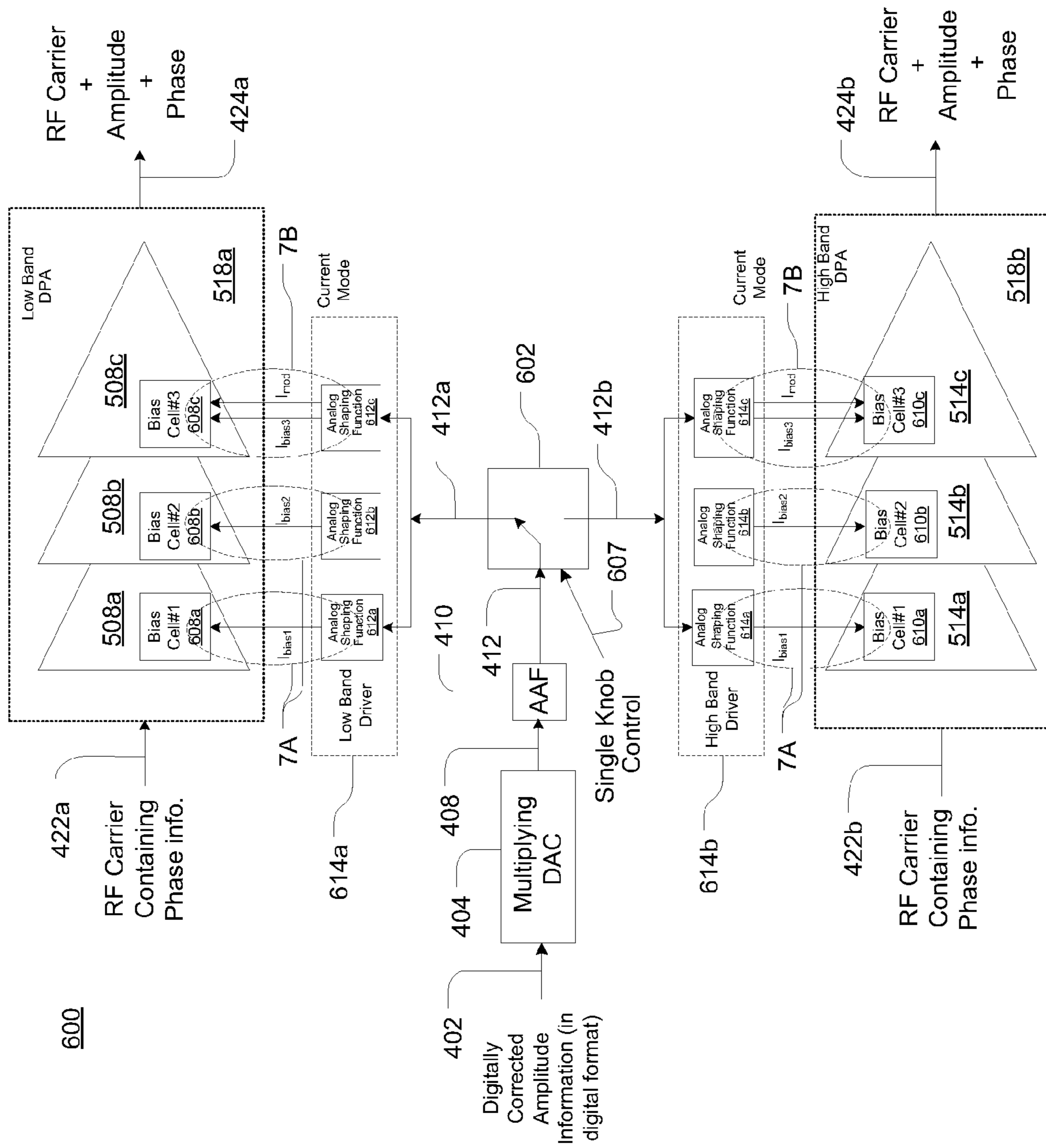


FIG. 6

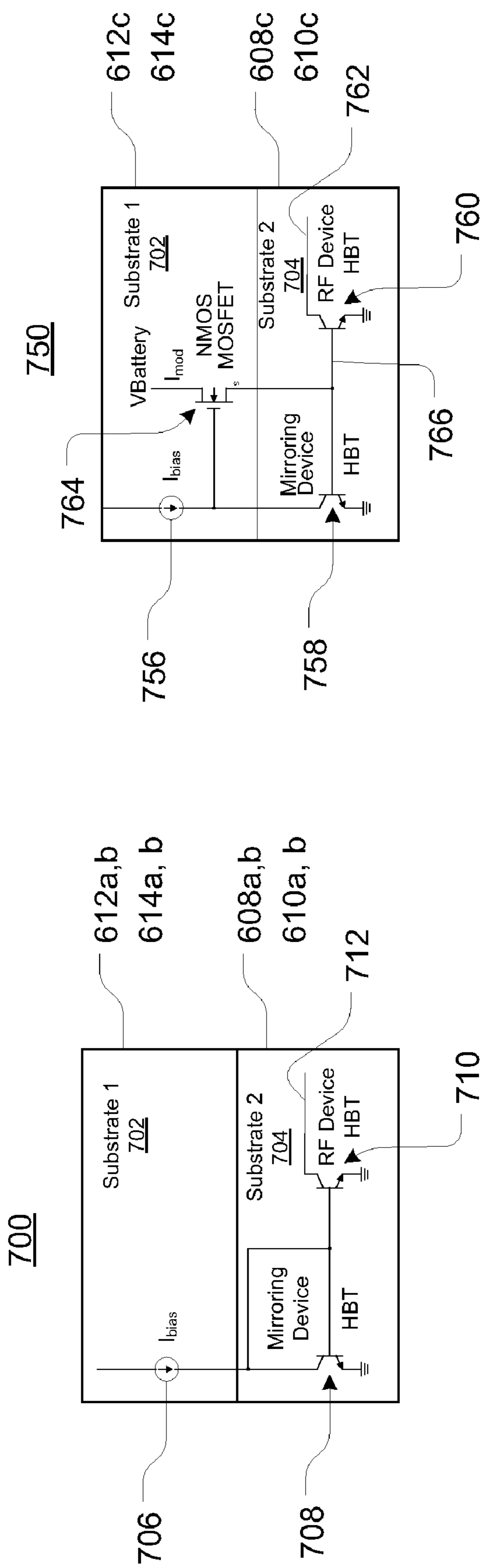


FIG. 7A

FIG. 7B



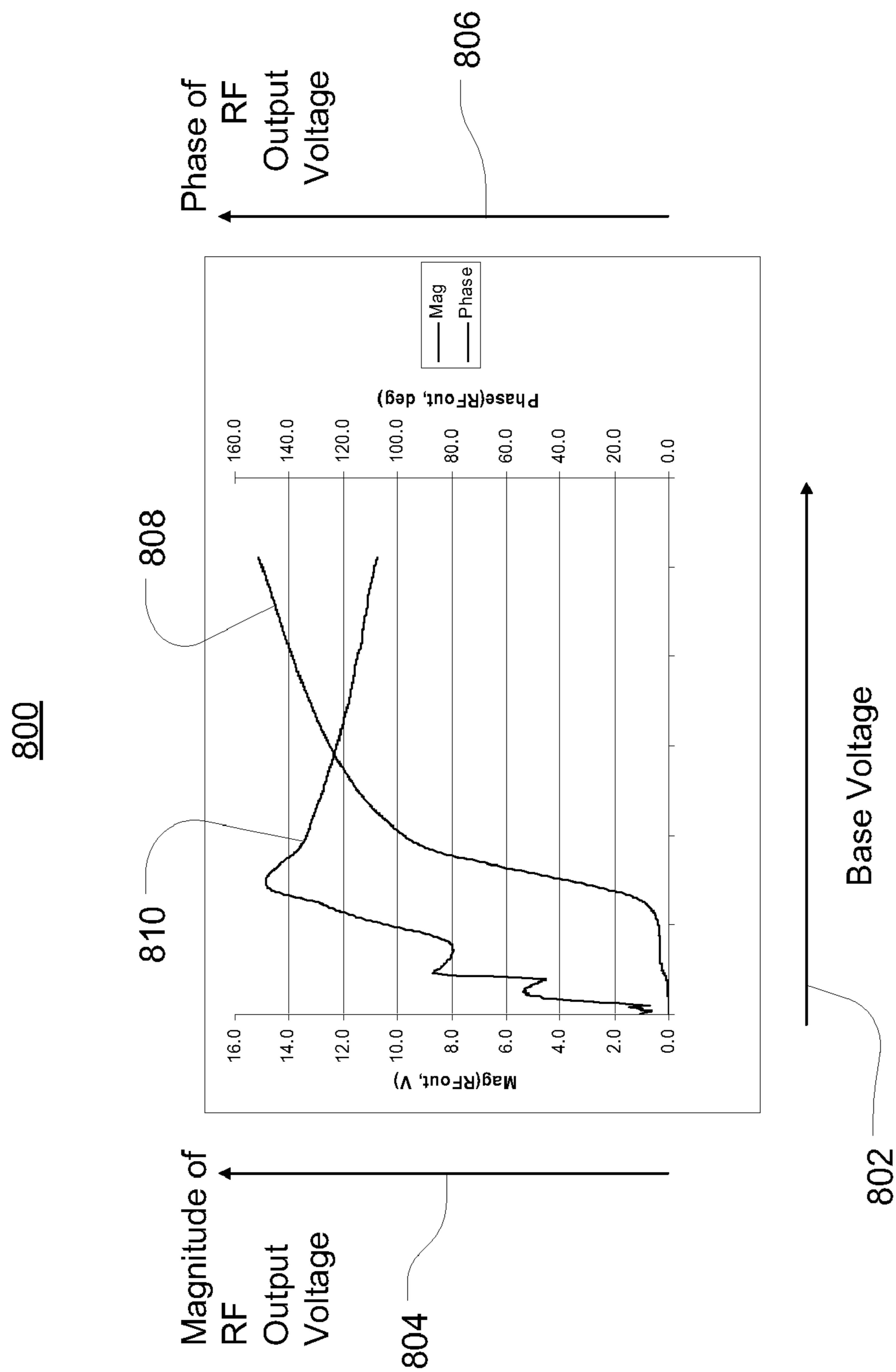


FIG. 8

900

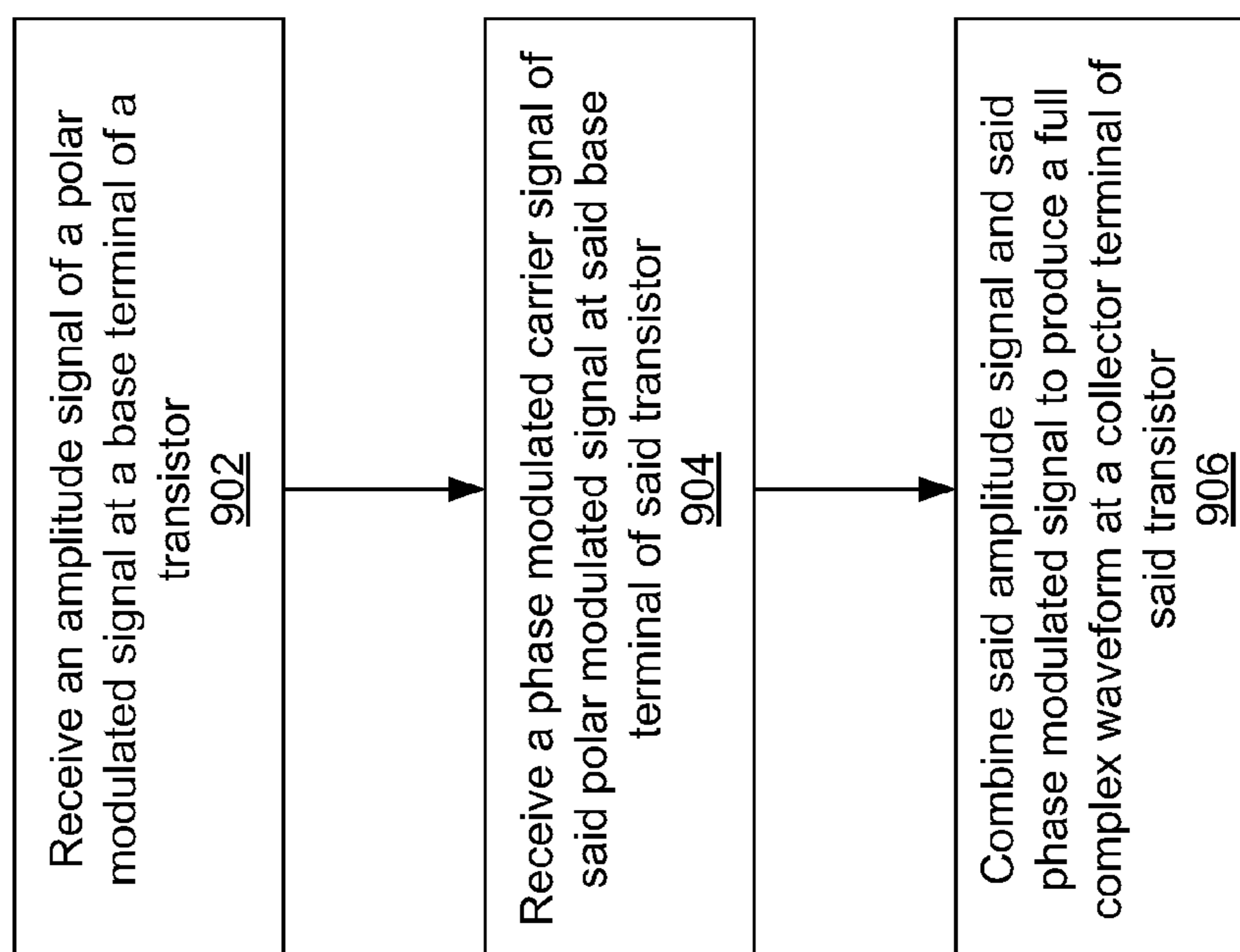


FIG. 9

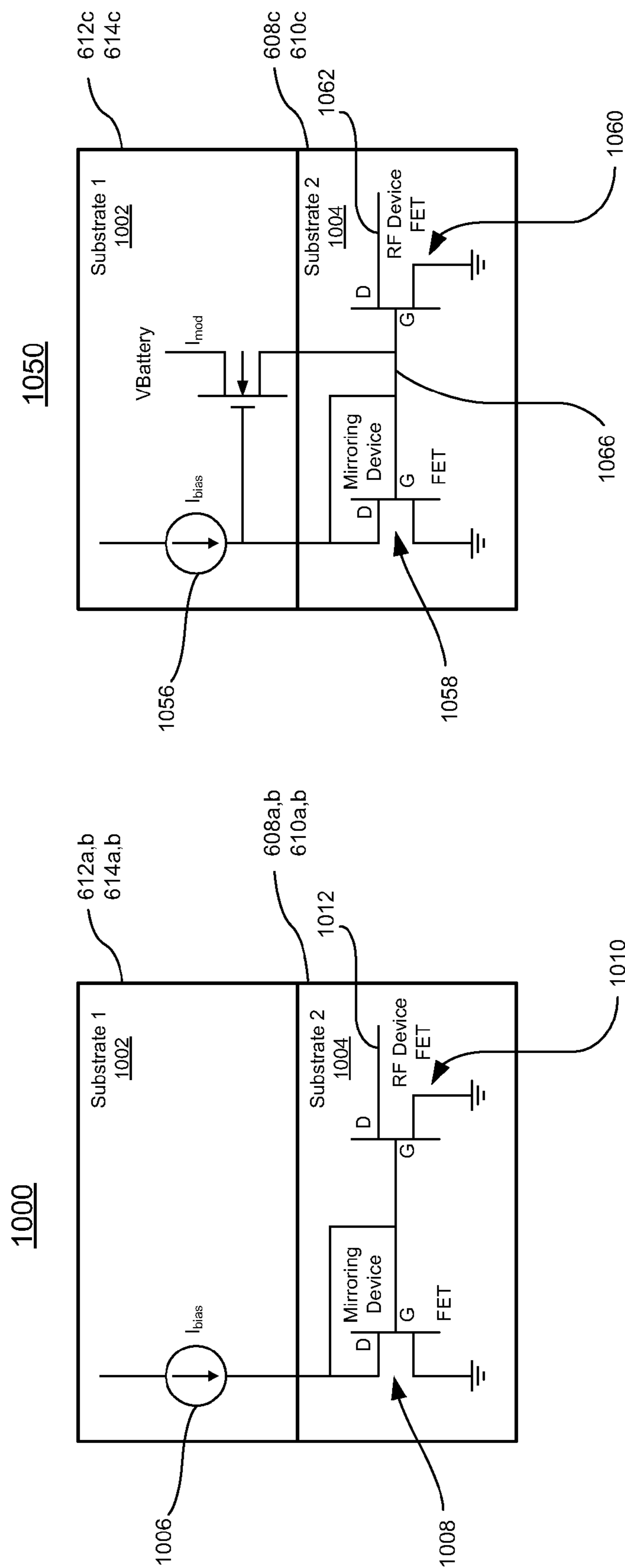


FIG. 10B

FIG. 10A

**APPARATUS, SYSTEM, AND METHOD FOR  
DIGITAL MODULATION OF POWER AMPLIFIER  
IN POLAR TRANSMITTER**

CROSS-REFERENCE TO RELATED  
APPLICATION

[0001] This is a continuation-in-part application of U.S. application Ser. No. 11/315,090, filed on Dec. 22, 2005, which is incorporated herein by reference in its entirety.

BACKGROUND

[0002] There are many benefits to using polar modulation as a means of transmitting information. Polar modulation makes possible the application of the amplitude modulation data signal at the very last stage of a transmitter before an antenna. As a result, all previous amplification stages may be operated in a constant envelope mode and can thus be biased very efficiently. Polar modulation also makes it possible to reduce the current drain quickly as the transmit power is reduced. Polar modulation provides clear talk-time benefits for wireless handset applications.

[0003] A common technique used to amplitude modulate a power amplifier includes modulating the power amplifier supply voltage. In the context of a power amplifier based on Gallium Arsenide (GaAs) heterojunction bipolar transistor (HBT) technology, amplitude modulation may be achieved by modulating the collector voltage applied to a HBT device (e.g., transistor) at the output stage of the power amplifier. Typically, the collector voltage may be modulated by introducing a metal oxide semiconductor (MOS) device in series with the power supply (e.g., the battery), which delivers the required current at a controlled voltage to the collector of the HBT device. The voltage drop across the MOS device, however, degrades the optimum efficiency that can be achieved relative to the situation with no MOS device. An additional drawback of the MOS device approach is that the modulation bandwidth that can be supported is limited by the both the capacitive loading associated with the large MOS device, and also by the closed-loop that is typically required to overcome the non-linear characteristic of the MOS device. Accordingly, there is a need for an alternate technique for amplitude modulation.

SUMMARY

[0004] In one embodiment, an apparatus comprises an amplifier to receive an amplitude signal of a polar modulated signal at a gate terminal of a transistor. The amplifier receives a phase modulated carrier signal of the polar modulated signal at the gate terminal of the transistor. The amplifier combines the amplitude signal and the phase modulated signal to produce a full complex waveform at a drain terminal of the transistor.

[0005] In one embodiment, an apparatus comprises a first amplifier to receive a first amplitude signal of a polar modulated signal at a gate terminal of a first transistor, to receive a first phase modulated carrier signal of the polar modulated signal at the gate terminal of the first transistor, and to combine the first amplitude signal and the first phase modulated signal to produce a first full complex waveform at a drain terminal of the first transistor.

[0006] In one embodiment, a system comprises a first antenna and a first amplifier coupled to the first antenna. The

first amplifier to receive a first amplitude signal of a polar modulated signal at a gate terminal of a first transistor, to receive a first phase modulated carrier signal of the polar modulated signal at the gate terminal of the first transistor, and to combine the first amplitude signal and the first phase modulated signal to produce a first full complex waveform at a drain terminal of the first transistor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. 1 illustrates one embodiment of a polar modulated transmitter comprising a digital segmented power amplifier.

[0008] FIG. 2 illustrates one embodiment of a polar modulated transmitter comprising a power amplifier controlled using a suitable digital base modulation technique.

[0009] FIG. 3 illustrates one embodiment of a polar modulated transmitter comprising power amplifier controlled using a suitable digital base modulation technique.

[0010] FIG. 4 illustrates one embodiment of a polar transmitter.

[0011] FIG. 5 illustrates one embodiment of a polar modulated transmitter comprising one embodiment of power amplifier and driver circuit to provide bias currents and voltages to power amplifier.

[0012] FIG. 6 illustrates one embodiment of a multi-mode polar transmitter.

[0013] FIG. 7A illustrates one embodiment of a bias interface circuit for first and second amplification stages of respective power amplifiers.

[0014] FIG. 7B illustrates one embodiment of a bias interface circuit for third amplification stages of respective power amplifiers.

[0015] FIG. 8 illustrates a graph of a transfer characteristic of measured AM-AM and AM-PM at high power without digital correction.

[0016] FIG. 9 illustrates one embodiment of a logic flow diagram.

[0017] FIG. 10A illustrates one embodiment of a bias interface circuit for first and second amplification stages of respective power amplifiers.

[0018] FIG. 10B illustrates one embodiment of a bias interface circuit for third amplification stages of respective power amplifiers.

DETAILED DESCRIPTION

[0019] In one embodiment, a technique to amplitude modulate a polar transmitter comprises modulating a transistor at the output stage of a power amplifier via a base terminal of the transistor rather than a collector terminal. In one embodiment, the amplifier transistor may be formed of GaAs HBT technology, for example. In a base modulation control technique, an MOS device may be provided in series with a base terminal of the output transistor rather than the collector terminal. Therefore, the voltage drop across the MOS device is eliminated and the efficiency performance of the transmitter may be improved. Furthermore, the intrinsic baseband to radio frequency (RF) transfer characteristics associated base modulation may exhibit linearity character-

istics that may be processed using any suitable pre-distortion or correction technique. The embodiments are not limited in this context.

[0020] In one embodiment, digital polar modulation techniques may comprise a high degree of digital content relative to analog polar modulation techniques. For example, a digital amplitude modulator may be implemented as a digital segmented power amplifier. Embodiments of digital segmented power amplifiers (also known as a radio frequency digital-to-analog converters or RFDACs) are discussed in commonly owned and commonly assigned United States Patent Application Publication Numbers US 2004/0247040, and US 2004/0247047, which are incorporated herein by reference. A digital segmented power amplifier may be controlled such that the digital envelope may be corrected in conjunction with digital phase correction techniques associated with a digital phase modulator. Embodiments of such digital envelope correction techniques are discussed in commonly owned and commonly assigned United States Patent Application Publication Number US 2004/0183635, which is incorporated herein by reference.

[0021] In one embodiment, digital processing techniques discussed herein may be combined with any suitable analog and/or digital circuits to obtain modulation across multiple modulation techniques. These modulation techniques may include, for example, Gaussian Mean Shift Keying (GMSK) used in GSM, Gaussian Frequency Shift Keying (GFSK) used in Digital European Cordless Telecommunications (DECT) and Bluetooth, Phase Shift Keying with eight states allowing for coding using 8-bit combinations (8-PSK) used in EDGE, Offset Quadrature Phase Shift Keying (OQPSK) and Hybrid Phase-Shift Keying (HPSK) used in IS-2000,  $\pi/4$  Differential Quadrature Phase-Shift Keying (DQPSK) used in Time Division Multiple Access (TDMA) and Orthogonal Frequency Division Modulation (OFDM) used in 802.11 and the like, among others. The embodiments are not limited in this context.

[0022] FIG. 1 illustrates one embodiment of a polar modulated transmitter 100 comprising a digital segmented power amplifier 128. Polar modulated transmitter 100 comprises digital correction and processing modules. These modules may be configured to render the various embodiments discussed herein suitable for complementary metal oxide semiconductor (CMOS) technology scaling. The digital correction and processing modules may be configured to convert input binary data into vector modulation of an RF carrier. In various embodiments, the vectors may be represented either in rectangular coordinate form in terms of an in-phase (I) component and a quadrature component (Q) or may be represented in polar form in terms of magnitude (R) and phase angle ( $\theta$ ). The I and Q components may be converted to polar components R and  $\theta$  using any suitable technique including, but not limited to, a CORDIC algorithm. The polar amplitude R and phase  $\theta$  components may be pre-distorted in a piecewise linear manner to compensate for non-linearity or distortion introduced into output signal 130 by power amplifier 128. The relative timing of the R and  $\theta$  paths also may be individually adjusted to compensate for delays introduced by the various circuit elements. The input data also may be processed by pulse shaping filters. The embodiments, however, are not limited in this context.

[0023] Data 102 is received at polar processing module 104. In one embodiment, data 102 may comprise rectangular

signal coordinates (e.g., I, Q) to be received and converted to polar signal coordinates (e.g., R,  $\theta$ ) by polar processing module 104. In one embodiment, polar processing module 104 may be implemented using any suitable conversion techniques, including a CORDIC algorithm. In one embodiment, polar processing module 104 converts input data 102 from rectangular coordinates (I, Q) to polar coordinates (R,  $\theta$ ) and produces output signals comprising an amplitude component 106 (e.g., R) and a phase component 108 (e.g.,  $\theta$ ). Amplitude component 106 and phase component 108 may be processed in separate paths. The embodiments are not limited in this context.

[0024] Amplitude component 106 may be provided to amplitude correction module 110. Amplitude component 106 may be provided in digital form comprising 2-N bits, where N represents any suitable number of bits to represent amplitude component 106 with adequate resolution and linearity. A higher number of bits produces a higher resolution amplitude component 106. In one embodiment, amplitude correction module 110 may be implemented as a distortion correction or modification module to correct amplitude non-linearity as a function of input amplitude (AM-AM) introduced into output signal 130 by power amplifier 128. AM-AM amplitude correction module 110 may be configured as a pre-distortion module to correct for non-linearity and distortion introduced by power amplifier 128 and timing correction for circuit timing delays. The AM-AM pre-distortion amplitude correction module 110 digitally pre-distorts the input amplitude using the input amplitude as the independent variable. The embodiments are not limited in this context.

[0025] Phase component 108 may be provided to phase correction module 112. Output signal 114 of amplitude correction module 110 also may be provided to phase correction module 112 to correct phase component 108 for any distortion caused by amplitude modulation. In one embodiment, phase correction module 112 may be implemented as a distortion correction or modification module to correct for phase shift as a function of input amplitude (AM-PM) introduced into output signal 130 by power amplifier 128. AM-PM distortion correction module 112 may be configured as a pre-distortion module to correct for non-linearity and distortion introduced by power amplifier 128 and timing corrections for circuit timing delays. The AM-PM pre-distortion phase correction module 112 digitally pre-distorts the input phase using the input phase as the independent variable. Phase output signal 116 from phase correction module 112 is provided to phase modulator 118. Phase modulated carrier signal 120 of phase modulator 118 is a phase modulated carrier and is provided to a phase input port of power amplifier 128. The embodiments are not limited in this context.

[0026] In one embodiment, power amplifier 128 may comprise 1-M amplification stages, where M is any suitable number of amplification stages. In one embodiment, power amplifier 128 may comprise three stages of amplification. Bias driver 126 biases the first and second stages. Output signal 114 of amplitude correction module 110 is provided to segment current driver 122. Segment current driver 122 drives the third stage of power amplifier 128 with amplitude modulation signal 124 to control the digital envelope of each of the amplitude segments. The third amplification stage may comprise, for example, a HBT device. Amplitude

modulation signal **124** may be applied to a base terminal of the HBT device in any suitable manner to implement one embodiment of base modulation techniques previously described. For example, modulation signal **124** may be applied to a transistor in series with the power supply and the base terminal of the HBT device. Power amplifier **128** combines phase modulated carrier signal **120** and amplitude modulation signal **124** to construct a full complex waveform output signal **130** at an output terminal thereof. The embodiments are not limited in this context.

[0027] FIG. 2 illustrates one embodiment of a polar modulated transmitter **200** comprising a power amplifier **214** controlled using a suitable digital base modulation technique. Polar modulated transmitter **200** comprises similar digital correction and processing modules as described above with respect to FIG. 1. For example, data **102** is received and converted by polar processing module **104**. Amplitude component **106** is processed by AM-AM correction module **110** and phase component **108** is processed by AM-PM correction module **112** along with amplitude component **114**. Phase output signal **116** is provided to phase modulator **118**. Phase modulated carrier signal **120** is provided to a phase input port of power amplifier **214**. The digital base modulation implementation for power amplifier **214** is similar to that discussed above with respect to digital segmented power amplifier **128**. One difference, however, is that at the final correction stage of AM-AM correction module **110**, the digital segment controls of amplitude component **114** that otherwise would be applied to a digital segmented power amplifier, instead are applied to a baseband digital-to-analog converter **202** (DAC). Analog signal **204** representative of amplitude component **114** is provided to anti-alias filter **206** (AAF). AAF **206** smooths out analog signal **204** output of DAC **202** to compensate for the non-linearity of the base modulation stage (e.g., third stage) of power amplifier **214**. Filtered signal **208** is provided to base current driver **210**. In various embodiments, output signal **204** or filtered signal **208** may be coupled to a base terminal of a single HBT device at an output stage of power amplifier **214** to implement base modulation techniques in a polar modulation environment. The embodiments are not limited in this context.

[0028] In one embodiment, power amplifier **214** may comprise 1-M amplification stages, where M is any suitable number of amplification stages. In one embodiment, power amplifier **214** may comprise three stages of amplification. Bias driver **126** biases the first and second stages. Current driver **210** drives the third stage of power amplifier **214** with amplitude modulation signal **212** to control the digital envelope of the amplitude signal. The third amplification stage may comprise, for example, a HBT device. Amplitude modulation signal **212** may be applied to a base terminal of the HBT device in any suitable manner to implement one embodiment of base modulation techniques previously described. Power amplifier **214** combines phase modulated carrier signal **120** and amplitude modulation signal **212** to construct a full complex waveform output signal **216** at an output terminal thereof. The embodiments are not limited in this context.

[0029] Polar modulated transmitter **200** comprising power amplifier **214** may be controlled using any suitable digital base modulation technique to implement various wireless standards. For example, polar modulated transmitter **200**

may be suitable in high linearity implementations. Accordingly, in one embodiment, a segmented stage of power amplifier **214** may no longer be segmented, but rather may comprise a single large HBT device, for example. The HBT device may be driven by a single control line with amplitude modulation signal **212**. In base modulation implementations, amplitude modulation signal **212** may be coupled to a base terminal of a single HBT device at an output stage of power amplifier **214**.

[0030] Controlling power amplifier **214** by driving HBT device over a single control line with amplitude modulation signal **212** enables several implementations of transmitter **200**. These implementations may comprise, for example, an output signal **216** envelope resolution that is not limited in by the physical number of segments in power amplifier **214**. Rather, the resolution may be defined by the bit-widths designated in digital correction module **110**, for example. In addition, there are no small time-domain transient effects in output signal **216** waveform due to segment switching effects. This provides increased linearity and noise performance. Furthermore, reducing the number of segment control lines to a single control line simplifies the baseband filtering associated with a digital segmented power amplifier, for example. The embodiments, however, are not limited in this context.

[0031] The application of amplitude modulation signal **124**, **212** to the base terminal of a HBT device in both digital segmented power amplifier **128** and power amplifier **214** supports a wide modulation bandwidth. In one embodiment, these implementations may support modulation bandwidths of several hundred MHz. Accordingly, the embodiments of transmitters **100**, **200** discussed above may be suitable for wideband applications such as WCDMA, for example. In other embodiments, extremely wide modulation bandwidth capability makes these control approaches suitable for multi-mode implementations of transmitters **100**, **200**, for example. The embodiments, however, are not limited in this context.

[0032] It will be appreciated that base modulation signals applied to the output stages of amplifiers **128**, **214** of respective polar architecture based transmitters **100**, **200** are not limited to digitally processed waveforms and associated baseband DAC **202** output signals along the envelope or amplitude control path **220**. Rather, the scope of the embodiments described herein is intended to cover the applications of analog control waveforms to a base terminal of the output stage of amplifiers **128**, **214**. For example, embodiments described herein cover the application of an analog waveform to a base terminal of an HBT device in the output stage of amplifiers **128**, **214** to implement the base modulation technique described herein.

[0033] FIG. 3 illustrates one embodiment of a polar modulated transmitter **300** comprising power amplifier **214** controlled using any suitable digital base modulation technique. The architecture of polar modulated transmitter **300** is substantially similar to the architecture of polar modulated transmitter **200** with the exception that the collector power supply terminal of a transistor in the output stage of power amplifier **214** is controlled by power converter **302**. In one embodiment, power converter **302** may be a DC-DC converter. Power converter **302** may be selected via power control input signal **304**. Power converter **302** is coupled to a power supply voltage **306**.

[0034] In general, use of power converter 302 on the collector supply terminal of a conventional power amplifier enables the collector voltage to be adjusted as a function of output power of amplifier 214. The efficiency of power amplifier 214 may be optimized when the power amplifier 214 is backed off from its maximum-rated power provided that power converter 302 is efficient. This efficiency enhancement technique also may be compatible with digital base amplitude modulation techniques used to control power amplifier 214. Accordingly, the combination of base modulation and collector power supply control further optimizes the efficiency of power amplifier 214 under backed off conditions.

[0035] FIG. 4 illustrates one embodiment of a polar transmitter 400. Polar transmitter 400 comprises multiplying DAC 404. Digitally corrected amplitude information 402 is applied to input ports of multiplying DAC 404. Digitally corrected amplitude information 402 may comprise 2-M bits, where M represents any suitable number of bits to resolve the amplitude information with a suitable resolution and linearity. Digitally corrected amplitude information 402 may be received from an output port of AM-AM correction module, such as, for example, amplitude correction module 110. In one embodiment, multiplying or scaling control signal 406 may be provided to an input port of multiplying DAC 404.

[0036] In one embodiment, analog output signal 408 may be applied to anti-aliasing filter 410 (AAF). Filtered analog amplitude signal 412 is applied to drivers 414a, 414b. Either driver 414a, b may be selected based on a particular mode (e.g., high band mode or low band mode) of operation of transmitter 400. Depending on the particular implementation, drivers 414a, b each may comprise multiple voltage mode or current mode drivers to drive respective digital power amplifiers 418a, b. The number may be proportional to the number of amplification stages of power amplifiers 418a, b. For example, power amplifiers 418a, b may include P amplification stages biased by P drivers, where P is any number. At least one of the amplification stages may include a transistor device (e.g., HBT device) to receive a modulated signal at a base terminal thereof. Accordingly, at least one of the drivers 414a, b may be configured to provide the modulation signal to the base terminal of the output transistor device.

[0037] In one embodiment, drivers 414a, b may be configured to operate in two or more different modes. For example, in GSM EDGE implementations, drivers 414a, b may be configured to drive both low band and high band digital power amplifiers. Accordingly, driver 414a may drive low band power amplifier 418a bias output signals 416a to provide suitable biasing for each amplification stage of low band power amplifier 418a. In addition, any one of bias output signals 416a may include an amplitude modulation signal, e.g., amplitude modulation signal 212, to control the digital envelope to be amplified by power amplifier 418a. Driver 414b may drive high band power amplifier 418b bias output signals 416b to provide suitable biasing for each amplification stage of power amplifier 418b. In addition, any one of bias output signals 416b may include an amplitude modulation signal, e.g., amplitude modulation signal 212, to control the digital envelope to be amplified by power amplifier 418b. The amplitude modulation signal may be applied to output amplification stages of power amplifiers

418a, b. In one embodiment, the amplitude modulation signal may be applied to a base terminal of a HBT device in any suitable manner to implement one embodiment of the base modulation techniques previously described.

[0038] In one embodiment, low band RF input signal 422a  $RF_{in_{low}}$  may be applied to an input port of low band digital power amplifier 418a. RF input signal 422a  $RF_{in_{low}}$  comprises an RF carrier containing phase modulation information. High band RF input signal 422b  $RF_{in_{high}}$  may be applied to an input port of high band digital power amplifier 418b. RF input signal 422b also may comprise an RF carrier containing phase modulation information. For example, signal 120 as discussed with respect to FIGS. 1-3. Each digital power amplifier 418a, b produces respective amplified RF output signals 424a, 424b. RF output signals 424a, b include RF carrier, signal amplitude, and phase information. Digital power amplifiers 418a, b are base modulated in at least one amplification stage to produce output signals 424a, b.

[0039] FIG. 5 illustrates one embodiment of a polar modulated transmitter 500 comprising one embodiment of power amplifier 518a including driver circuit 514a to drive bias currents and voltages to power amplifier 518a. Polar modulated transmitter 500 is a portion of a multi-mode transmitter where only the low band digital power amplifier portion is shown. Accordingly, in one embodiment of multi-mode polar modulated transmitter 500, power amplifier 518a may be a low band digital power amplifier. Power amplifier 518a may be a RF DAC adapted for telecommunications implementations. For example, in one embodiment, power amplifier 518a may be adapted as a low band RF digital power amplifier for GSM EDGE implementations. In one embodiment, power amplifier 518a comprises three amplification stages including a first amplification stage 508a, a second amplification stage 508b, and a third amplification stage 508c. Low band RF input signal 422a  $RF_{in_{low}}$  comprising an RF carrier containing phase modulation information may be applied to an input port of first amplification stage 508a. RF output signal 424a may be applied to antenna or to other amplification stages or circuit elements.

[0040] In one embodiment, driver 514a comprises three bias modules 502a, 502b, 502c to drive respective bias currents or supply voltages 510a, 510b, 510c to bias respective amplification stages 508a, 508b, 508c. Digitally corrected amplitude information 402 may be received from an output port of AM-AM correction module, such as, for example, amplitude correction module 110. In one embodiment, multiplying DAC 404 also may receive multiplying or scaling control signal 406 at an input port of multiplying DAC 404. In one embodiment, analog output signal 408 may be applied to anti-aliasing filter 410 (AAF). As previously described, AAF 410 smooths out analog signal 408 output of multiplying DAC 404 to compensate for the non-linearity of third amplification stage 508c (e.g., the base modulation stage) of power amplifier 518a. Filtered analog amplitude signal 412 of AAF 410 forms the input to each bias module 502a-c. Bias modules 502a-c may be configured to operate either in current mode or voltage mode to drive bias current or supply voltage in linear or non-linear (e.g., square) proportions. For example, bias module 502a may be configured to operate in fast-linear current mode and bias modules 502b, c may be configured to operate in linear voltage mode. In addition, each bias module 502a-c may be

configured to implement analog shaping functions. At least one of bias modules **502a-c** may be adapted to provide a modulation signal to a base terminal of a transistor in any one of amplification stages **508a-c** to implement a base modulation technique in accordance with the various embodiments described herein. For example, in one embodiment, bias module **508c** may be configured to modulate a power amplifier transistor via a base terminal of the transistor rather than a collector terminal. In one embodiment, the amplifier transistor may be formed of GaAs HBT technology, for example, and bias module **508c** may be configured to provide modulation signal **510c** to drive the base terminal of an HBT transistor in third amplification stage **508c** (e.g., the output stage of power amplifier **518a**).

[0041] FIG. 6 illustrates one embodiment of a multi-mode polar transmitter **600**. Multi-mode polar transmitter **600** comprises multiplying DAC **404**. Digitally corrected amplitude information **402** is applied to input ports of multiplying DAC **404**. Digitally corrected amplitude information **402** may comprise 2-M bits, where M represents any suitable number of bits to resolve the amplitude information with a suitable resolution and linearity. In one embodiment, digitally corrected amplitude information **402** may be received from an output port of AM-AM correction module, such as, for example, amplitude correction module **110**.

[0042] In one embodiment, analog output signal **408** may be applied to AAF **410**. Filtered analog amplitude signal **412** may be applied to mode select switch **602**. Mode select switch **602** may be controlled via single knob control signal **607**. Mode select switch routes filtered analog amplitude signal **412** to either low band or high digital power amplifiers **518a** or **518b**, respectively. As previously discussed, in one embodiment, power amplifier **518a** may be adapted as a low band RF digital power amplifier for GSM EDGE implementations. Likewise, in one embodiment, power amplifier **518b** may be adapted as a high band RF digital power amplifier for GSM EDGE implementations. Accordingly, low band waveforms **412a** are routed to low band digital power amplifier **518a** and high band waveforms **412b** are routed to high band digital power amplifier **518b** through respective low band driver **614a** and high band driver **614b** based on the selection of single knob control signal **607**. Either low band driver **614a** or high band driver **614b** may be selected based on the particular mode of operation of transmitter **600** (e.g., high band mode or low band mode). Low band digital power amplifier **518a** receives input signal **422a**, which comprises and RF carrier containing phase information. High band digital power amplifier **518b** receives input signal **422b**, which comprises and RF carrier containing phase information.

[0043] In one embodiment, low band driver **614a** may comprise multiple current mode driver modules **612a**, **612b**, **612c** to bias respective bias cells **608a**, **608b**, **608c** of low band digital power amplifier **518a** amplification stages **508a**, **508b**, **508c**, respectively. In one embodiment, current mode driver modules **612a-c** may be configured to shape the analog waveforms of analog input signal **412a**. In one embodiment, current mode driver modules **612a-c** supply bias current  $I_{bias}$  to respective bias cells **608a-c**. Current mode driver module **612a** generates bias current  $I_{bias1}$  to bias cell **608a** of amplification stage **508a**. Current mode driver module **612b** generates bias current  $I_{bias2}$  to bias cell **608b** of amplification stage **508b**. Current mode driver module **612c**

generates bias current  $I_{bias3}$  to bias cell **608c** of amplification stage **508c**. In addition current mode driver module **612c** also generates modulation current signal  $I_{mod}$  to the output stage of bias cell **608c**.  $I_{mod}$  represents amplitude modulation signal based on digitally corrected amplitude information **402**.  $I_{mod}$  may be applied to the base terminal of an amplifier transistor (e.g., HBT device) in amplification stage **508c**, for example. Detailed views of one embodiment of bias interfaces **7A** and **7B** are shown in FIGS. **7A** and **7B**.

[0044] In one embodiment, high band driver **614b** may comprise multiple current mode driver modules **614a**, **614b**, **614c** to bias respective bias cells **610a**, **610b**, **610c** of high band power amplifier **518b** amplification stages **514a**, **514b**, **514c**, respectively. In operation high band driver **614a** and power amplifier **518a**, including amplification stages **514a-c** and respective bias cells **610a**, **610b**, **610c** operate in a manner similar to that described above with respect to low band digital power amplifier **518a**.

[0045] Output signals **424a**, **b** may be provided to an antenna for transmission or may be provided to other circuit elements. Each output signal **424a**, **b** comprises RF carrier, amplitude, and phase information.

[0046] FIG. 7A illustrates one embodiment of a bias interface circuit for first and second amplification stages **508a**, **b** and **514a**, **b** of respective power amplifiers **518a**, **b**. Bias interface circuit **700** represents one embodiment of current mode driver modules **612a**, **b**, **614a**, **b** and bias cells **608a**, **b**, **610a**, **b**. Bias interface circuit **700** may be configured to drive bias currents  $I_{bias1}$  and  $I_{bias2}$  between current mode driver modules **612a**, **612b** formed on first substrate **702** and bias cells **608a**, **608b** formed on second substrate **704**. First substrate may be formed of Silicon (Si) and second substrate may be formed of Gallium Arsenide (GaAs), for example.

[0047] In one embodiment, bias interface circuit **700** comprises current source **706** to drive  $I_{bias}$  from current mode driver modules **612a**, **b**, **614a**, **b** to respective bias cells **608a**, **b**, **610a**, **b**. In one embodiment, bias cells **608a**, **b**, **610a**, **b** comprise mirroring device **708** and RF device **710**. Mirroring device **708** drives  $I_{bias}$  in the output collector **712** terminal of RF device **710**. Both mirroring device **708** and RF device **710** may be HBT devices.

[0048] FIG. 7B illustrates one embodiment of a bias interface circuit for third amplification stages **508c**, **514c** of respective power amplifiers **518a**, **b**. Bias interface circuit **750** represents one embodiment of current mode driver modules **612c**, **614c** and bias cells **608c**, **610c**. Bias interface circuit **750** may be configured to drive bias current  $I_{bias3}$  and modulation current  $I_{mod}$  between current mode driver module **612c** formed on first substrate **702** and bias cell **608c** formed on second substrate **704**. As previously discussed, first substrate may be formed of Si and second substrate may be formed of GaAs, for example.

[0049] In one embodiment, bias interface circuit **750** comprises current source **756** to drive  $I_{bias3}$  from current mode driver module **612c** to bias cell **608c**. In one embodiment, bias cell **608c** comprises mirroring device **758** and RF device **760**. Mirroring device **758** drives  $I_{bias3}$  in the output collector terminal **762** of RF device **760**. Both mirroring device **758** and RF device **760** may be HBT devices. Modulation current  $I_{mod}$  may be driven by transistor device



**764** into base terminal **766** of RF device **760**. In one embodiment, transistor device **764** may be an N-MOS MOSFET transistor device. Collector terminal **762** is coupled to outputs of respective power amplifiers **518a, b** to generate respective amplified RF output signals **424a, 424b**. As shown the base current of HBT device **760** may be modulated by introducing N-MOS MOSFET transistor device **764** in series with base terminal **766** of HBT device **760** and the power supply (e.g., battery), which delivers the required current at a controlled voltage into base terminal **766** of HBT device **760**. In this configuration, there is no voltage drop in the collector terminal of HBT device **760**. Therefore, there is no degradation of the optimum efficiency that can be achieved relative to the situation where a MOS device. Furthermore, the modulation bandwidth that can be supported is not limited by the capacitive loading associated with the large MOS device, and is not limited by the closed-loop that is typically required to overcome the non-linear characteristic of the MOS device.

[0050] FIG. 8 illustrates a graph **800** of a transfer characteristic of measured AM-AM and AM-PM at high power without digital correction. The characteristics are measured as function of base voltage applied to base **766** of transistor **760**. Horizontal axis **802** represents base voltage. First vertical axis **804** represents the magnitude of RF output voltage in terms of voltage (e.g., **424a, b**) as a function of base **766** voltage. Second vertical axis **806** represents the phase of RF output voltage in terms of degrees (e.g., **424a, b**) as a function of base **766** voltage. Magnitude of RF output voltage waveform **808** and phase of RF output voltage waveform **810** are shown as a function of base **766** voltage.

[0051] Operations for the above system and subsystem may be further described with reference to the following figures and accompanying examples. Some of the figures may include programming logic. Although such figures presented herein may include a particular programming logic, it can be appreciated that the programming logic merely provides an example of how the general functionality described herein can be implemented. Further, the given programming logic does not necessarily have to be executed in the order presented unless otherwise indicated. In addition, the given programming logic may be implemented by a hardware element, a software element executed by a processor, or any combination thereof. The embodiments are not limited in this context.

[0052] FIG. 9 illustrates one embodiment of a logic flow diagram **900**. Accordingly, a power amplifier **518a** may be configured to receive (**902**) an amplitude signal **412a** of a polar modulated signal **402** at a base terminal **766** of a transistor **760**. Power amplifier **518a** receives (**904**) a phase modulated carrier signal **422a** of the polar modulated signal **402** at the base terminal **766** of the transistor **760**. Power amplifier **518a** combines (**906**) the amplitude signal **412a** and the phase modulated signal **422a** to produce a full complex waveform **424a** at a collector terminal **762** of the transistor **760**.

[0053] In one embodiment, the amplitude signal **412a** may be pre-distorted by amplitude correction module **110** to compensate for non-linearity of transistor **760**. Further, the phase modulated carrier signal **422a** may be pre-distorted by phase correction module **112** to compensate for non-linearity of the transistor **760**.

[0054] In one embodiment, digital segment control signals may be received at an input portion of a digital to analog converter and a polar modulated signal may be produced at an output portion of the digital to analog converter.

[0055] In one embodiment, a power supply signal may be received by transistor **764** and may be combined with the phase modulated carrier signal **422a** and the amplitude signal **412a** by transistor **760**. The voltage at the collector terminal **762** of the transistor **760** may be adjusted under backed off conditions in accordance with output power of the transistor **760**.

[0056] For purposes of illustration, the above description has been provided in the context of polar transmitter architectures. For instance, examples have been provided that involve HBT-based power amplifiers. However, the embodiments are not limited to HBT or any type of Bi-Polar transistor. In fact, other transistor technologies may be used.

[0057] For instance, embodiments may employ field effect transistor (FET) technology. For such embodiments, FETs may be substituted for bi-polar transistors. Moreover, connections to FET gate terminals may be substituted for connections to bi-polar transistor base terminals. Also, connections to FET drain terminals may be substituted for connections bi-polar transistor collector terminals.

[0058] Examples of such substitutions are provided in FIGS. 10A and 10B. These drawings, like FIGS. 7A and 7B, illustrate exemplary bias interface circuits. However, instead of employing bipolar HBTs, the circuits of FIGS. 10A and 10B employ FETs.

[0059] In particular, FIG. 10A illustrates one embodiment of a bias interface circuit **1000** for first and second amplification stages **508a, b** and **514a, b** of respective power amplifiers **518a, b**. Bias interface circuit **1000** represents one embodiment of current mode driver modules **612a, b, 614a, b** and bias cells **608a, b, 610a, b**. Bias interface circuit **1000** may be configured to drive bias currents  $I_{bias1}$  and  $I_{bias2}$  between current mode driver modules **612a, 612b** formed on first substrate **1002** and bias cells **608a, 608b** formed on second substrate **1004**. First substrate may be formed of Silicon (Si) and second substrate may be formed of Gallium Arsenide (GaAs), for example. However, the embodiments are not limited to this example.

[0060] In one embodiment, bias interface circuit **1000** comprises current source **1006** to drive  $I_{bias}$  from current mode driver modules **612a, b, 614a, b** to respective bias cells **608a, b, 610a, b**. In one embodiment, bias cells **608a, b, 610a, b** comprise mirroring device **1008** and RF device **1010**. Mirroring device **1008** drives  $I_{bias}$  in the output drain **1012** terminal of RF device **1010**. Both mirroring device **1008** and RF device **1010** may be FET devices.

[0061] FIG. 10B illustrates one embodiment of a bias interface circuit **1050** for third amplification stages **508c, 514c** of respective power amplifiers **518a, b**. Bias interface circuit **1050** represents one embodiment of current mode driver modules **612c, 614c** and bias cells **608c, 610c**. Bias interface circuit **1050** may be configured to drive bias current  $I_{bias3}$  and modulation current  $I_{mod}$  between current mode driver module **612c** formed on first substrate **1002** and bias cell **608c** formed on second substrate **1004**. As previously discussed, first substrate may be formed of Si and

second substrate may be formed of GaAs, for example. However, other substrate types may be employed.

[0062] In one embodiment, bias interface circuit **1050** comprises current source **1056** to drive  $I_{\text{bias}3}$  from current mode driver module **612c** to bias cell **608c**. In one embodiment, bias cell **608c** comprises mirroring device **1058** and RF device **1060**. Mirroring device **1058** drives  $I_{\text{bias}3}$  in the output drain terminal **1062** of RF device **1060**. Both mirroring device **1058** and RF device **1060** may be FET devices. Modulation current  $I_{\text{mod}}$  may be driven by transistor device **1064** into gate terminal **1066** of RF device **1060**. In one embodiment, transistor device **1064** may be an N-MOS MOSFET transistor device. Drain terminal **1062** is coupled to outputs of respective power amplifiers **518a, b** to generate respective amplified RF output signals **424a, 424b**. As shown the gate current of FET device **1060** may be modulated by introducing N-MOS MOSFET transistor device **1064** in series with gate terminal **1066** of FET device **1060** and the power supply (e.g., battery), which delivers the required current at a controlled voltage into gate terminal **1066** of FET device **1060**. In this configuration, there is no voltage drop in the drain terminal of FET device **1060**. Therefore, there is no degradation of the optimum efficiency that can be achieved relative to the situation where a MOS device. Furthermore, the modulation bandwidth that can be supported is not limited by the capacitive loading associated with the large MOS device, and is not limited by the closed-loop that is typically required to overcome the non-linear characteristic of the MOS device.

[0063] The disclosure herein provides various examples involving modulation. Some of these examples involve three stages, in which base/gate modulation is performed at a third stage. However, it is important to note that various numbers of stages may be employed. Also, gate and/or base modulation, as described herein, may be performed and implemented at any one of such stages. Moreover, gate and/or base modulation may be performed and implemented at any combination of two or more such stages. Thus, the embodiments are not limited to the examples provided herein. Moreover, techniques described herein may be employed with polar modulation as well as other modulation types.

[0064] Numerous specific details have been set forth herein to provide a thorough understanding of the embodiments. It will be understood by those skilled in the art, however, that the embodiments may be practiced without these specific details. In other instances, well-known operations, components and circuits have not been described in detail so as not to obscure the embodiments. It can be appreciated that the specific structural and functional details disclosed herein may be representative and do not necessarily limit the scope of the embodiments.

[0065] It is also worthy to note that any reference to “one embodiment” or “an embodiment” means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment. The appearances of the phrase “in one embodiment” in various places in the specification are not necessarily all referring to the same embodiment.

[0066] Some embodiments may be implemented using an architecture that may vary in accordance with any number of factors, such as desired speed, power levels, heat tolerances, semiconductor manufacturing processing, input rates, output rates, memory resources, and other performance constraints.

[0067] Some embodiments may be described using the expression “coupled” along with their derivatives. It should be understood that the term “coupled” may be used to indicate that two or more elements are in direct physical or electrical contact. The term “coupled,” however, also may mean that two or more elements are not in direct contact with each other, but yet still co-operate or interact with each other. The embodiments are not limited in this context.

[0068] While certain features of the embodiments have been illustrated as described herein, many modifications, substitutions, changes and equivalents will now occur to those skilled in the art. It is therefore to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the embodiments.

1. A method, comprising:

receiving an amplitude signal of a polar modulated signal at a gate terminal of a transistor;

receiving a phase modulated carrier signal of said polar modulated signal at said gate terminal of said transistor; and

combining said amplitude signal and said phase modulated signal to produce a full complex waveform at a drain terminal of said transistor.

2. The method of claim 1, comprising pre-distorting said amplitude signal to compensate for non-linearity of said transistor.

3. The method of claim 1, comprising pre-distorting said phase modulated carrier signal to compensate for non-linearity of said transistor.

4. The method of claim 1, comprising:

receiving digital segment control signals at an input portion of a digital to analog converter; and

producing said polar modulated signal at an output portion of said digital to analog converter.

5. The method of claim 1, comprising:

receiving a power supply signal; and

combining said phase modulated carrier signal and said amplitude signal with said power supply signal.

6. The method of claim 5, comprising:

adjusting a voltage at a drain terminal of said transistor under backed off conditions in accordance with output power of said transistor.

7. An apparatus, comprising:

a first amplifier to receive a first amplitude signal of a polar modulated signal at a gate terminal of a first transistor; to receive a first phase modulated carrier signal of said polar modulated signal at said gate terminal of said first transistor; and to combine said first amplitude signal and said first phase modulated signal to produce a first full complex waveform at a drain terminal of said first transistor.

8. The apparatus of claim 7, comprising an amplitude correction module to pre-distort said amplitude signal to compensate for non-linearity of said transistor.

9. The apparatus of claim 7, comprising a phase correction module to pre-distort said first phase modulated carrier signal to compensate for non-linearity of said first transistor.

**10.** The apparatus of claim 7, comprising a digital to analog converter to receive digital segment control signals at an input portion to produce said polar modulated signal at an output portion of said digital to analog converter.

**11.** The apparatus of claim 7, comprising an interface module to receive a power supply signal and to combine said first phase modulated carrier signal and said first amplitude signal with said power supply signal.

**12.** The apparatus of claim 11, wherein said interface module is to adjust a voltage at a drain terminal of said first transistor under backed off conditions in accordance with output power of said first transistor.

**13.** The apparatus of claim 7, comprising:

a second amplifier to receive a second amplitude signal of said polar modulated signal at a gate terminal of a second transistor; to receive a second phase modulated carrier signal of said polar modulated signal at said gate terminal of said second transistor; and to combine said second amplitude signal and said second phase modulated signal to produce a second full complex waveform at a drain terminal of said second transistor.

**14.** The apparatus of claim 13, comprising a mode select switch to select either said first amplifier or said second amplifier.

**15.** An system, comprising:

a first antenna; and

a first amplifier coupled to said first antenna, said first amplifier to receive a first amplitude signal of a polar modulated signal at a gate terminal of a first transistor; to receive a first phase modulated carrier signal of said polar modulated signal at said gate terminal of said first transistor; and to combine said first amplitude signal and said first phase modulated signal to produce a first full complex waveform at a drain terminal of said first transistor.

**16.** The system of claim 15, comprising an amplitude correction module to pre-distort said amplitude signal to compensate for non-linearity of said transistor.

**17.** The system of claim 15, comprising a phase correction module to pre-distort said first phase modulated carrier signal to compensate for non-linearity of said first transistor.

**18.** The system of claim 15, comprising a digital to analog converter to receive digital segment control signals at an input portion to produce said polar modulated signal at an output portion of said digital to analog converter.

**19.** The system of claim 15, comprising an interface module to receive a power supply signal and to combine said first phase modulated carrier signal and said first amplitude signal with said power supply signal.

**20.** The system of claim 19, wherein said interface module is to adjust a voltage at a drain terminal of said first transistor under backed off conditions in accordance with output power of said first transistor.

**21.** The system of claim 15, comprising:

a second antenna; and

a second amplifier coupled to said second antenna, said second amplifier to receive a second amplitude signal of said polar modulated signal at a gate terminal of a second transistor; to receive a second phase modulated carrier signal of said polar modulated signal at said gate terminal of said second transistor; and to combine said second amplitude signal and said second phase modulated signal to produce a second full complex waveform at a drain terminal of said second transistor.

**22.** The system of claim 21, comprising a mode select switch to select either said first amplifier or said second amplifier.

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