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(54) **BANDGAP REFERENCE GENERATION FOR MULTIPLE POWER SUPPLY DOMAINS**

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(21) Appl. No.: **19/191,314**

(22) Filed: **Apr. 28, 2025**

Related U.S. Application Data

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Publication Classification

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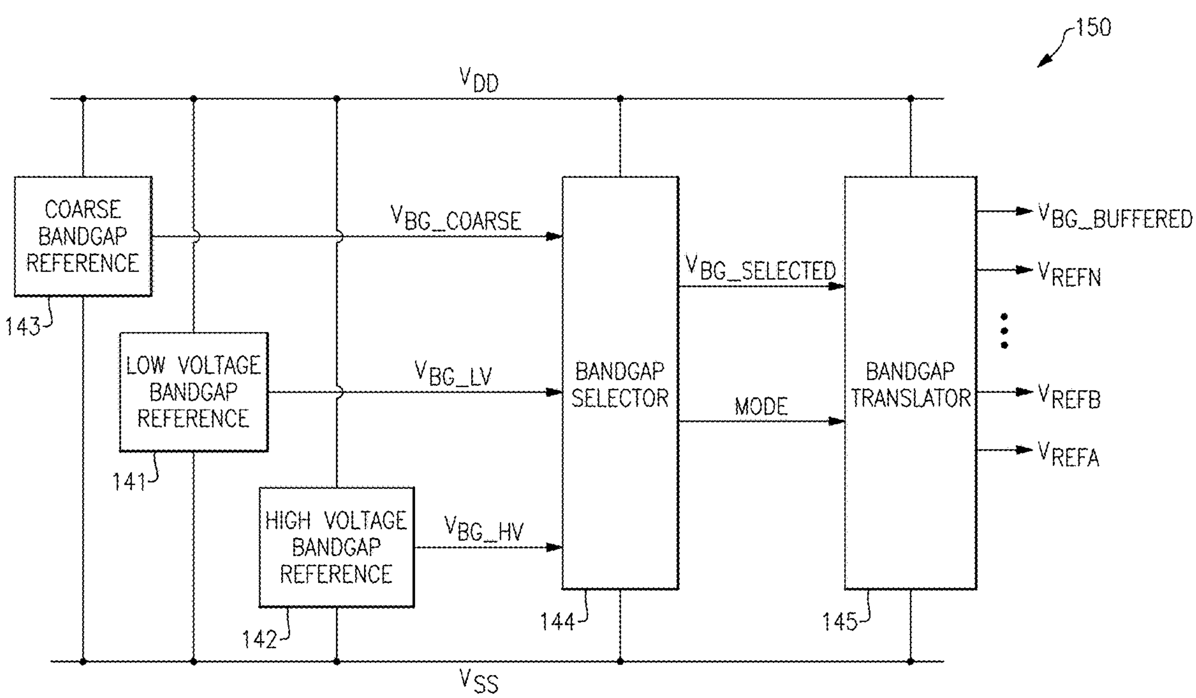
G05F 3/30 (2006.01)

(52) **U.S. Cl.**
CPC *G05F 3/30* (2013.01)

(57) **ABSTRACT**

Apparatus and methods for bandgap reference generators are disclosed. In certain embodiments, a bandgap reference generator includes a low voltage bandgap reference circuit that generates a first bandgap reference voltage, a high voltage bandgap reference circuit that generates a second bandgap reference voltage, a bandgap selector circuit that outputs the first bandgap reference voltage or the second bandgap reference voltage as a selected bandgap reference voltage based on a voltage level of the power supply voltage, and a bandgap translator circuit that generates an output bandgap reference voltage based on the selected bandgap reference voltage.



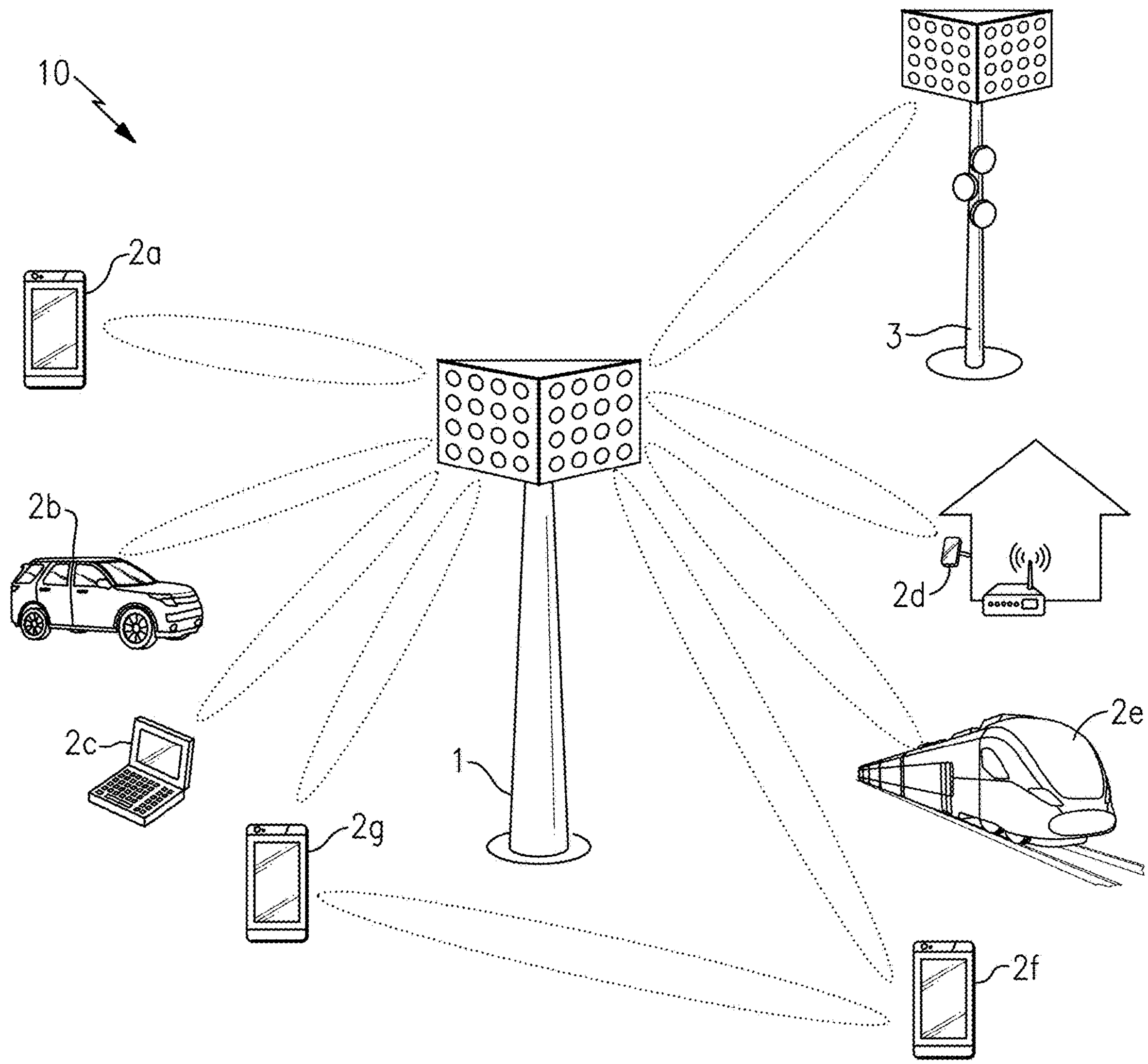
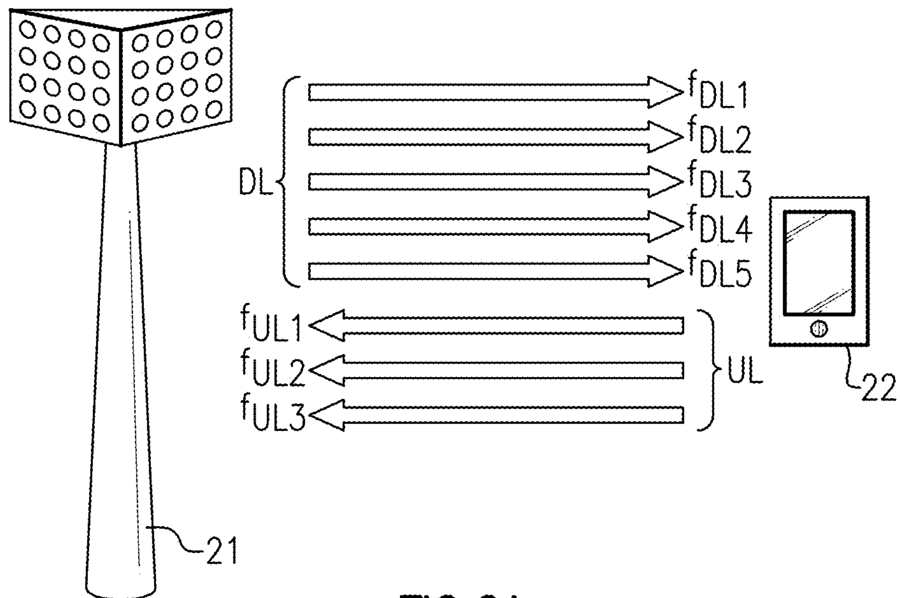
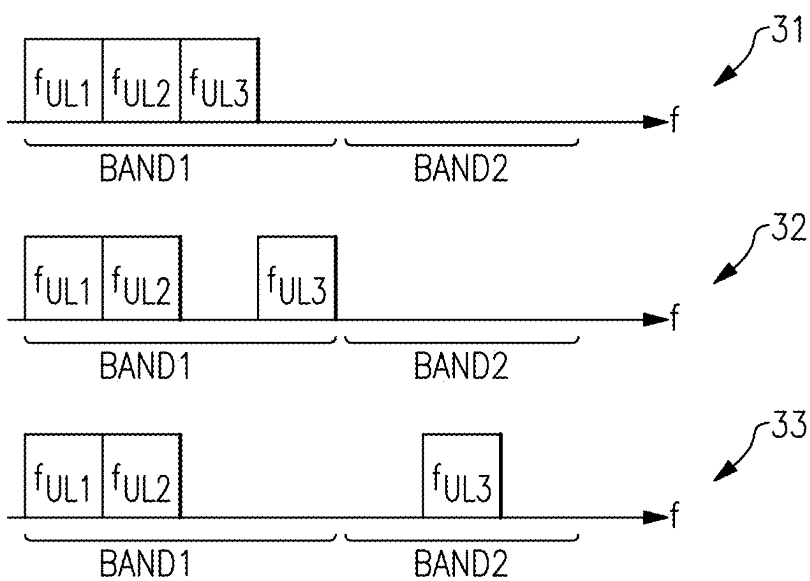


FIG.1



DL
f_{DL1}
f_{DL2}
f_{DL3}
f_{DL4}
f_{DL5}
f_{UL1}
f_{UL2}
f_{UL3}
UL
22
21

FIG.2A



31
f_{UL1} f_{UL2} f_{UL3}
f
BAND1
BAND2
32
f_{UL1} f_{UL2} f_{UL3}
f
BAND1
BAND2
33
f_{UL1} f_{UL2} f_{UL3}
f
BAND1
BAND2

FIG.2B

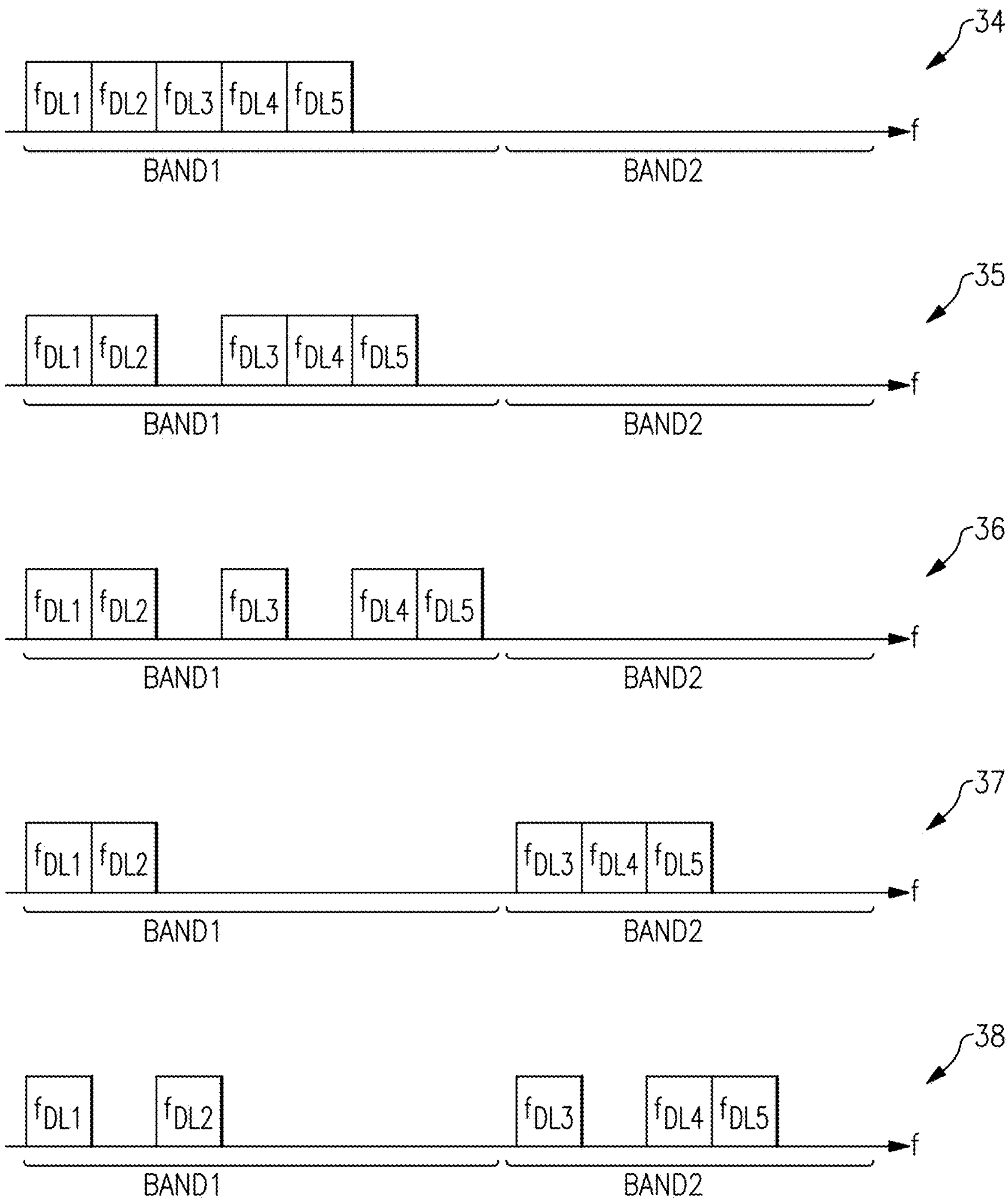

34
fDL1
fDL2
fDL3
fDL4
fDL5
f
BAND1
BAND2
35
fDL1
fDL2
fDL3
fDL4
fDL5
f
BAND1
BAND2
36
fDL1
fDL2
fDL3
fDL4
fDL5
f
BAND1
BAND2
37
fDL1
fDL2
fDL3
fDL4
fDL5
f
BAND1
BAND2
38
fDL1
fDL2
fDL3
fDL4
fDL5
f
BAND1
BAND2

FIG.2C

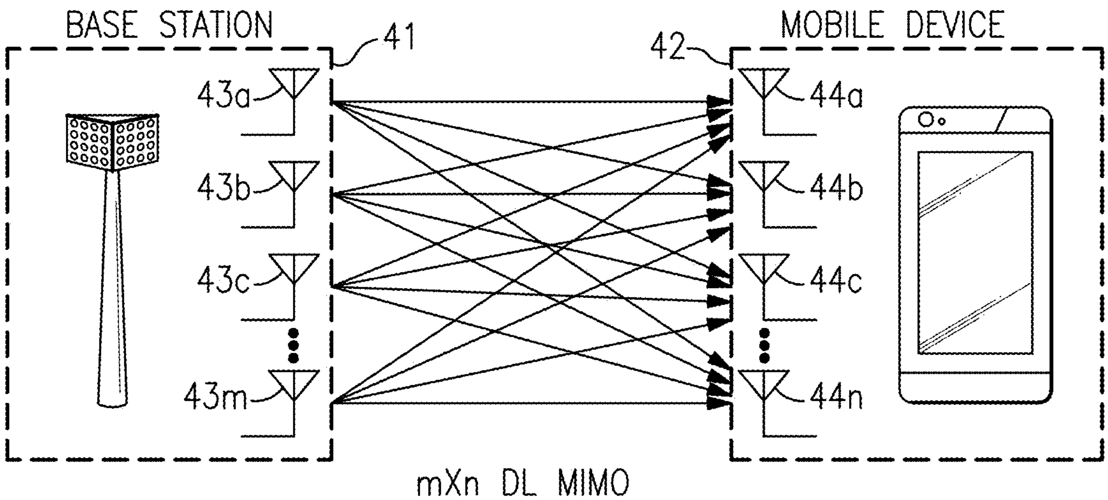

BASE STATION
41
42
MOBILE DEVICE
43a
43b
43c
43m
44a
44b
44c
44n
mXn DL MIMO

FIG.3A

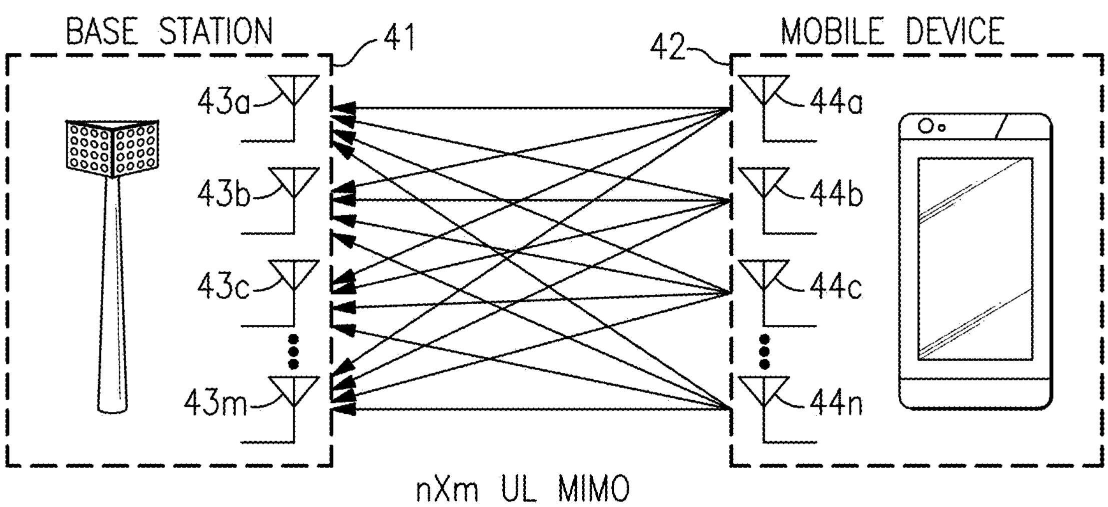

BASE STATION
41
42
MOBILE DEVICE
43a
43b
43c
43m
44a
44b
44c
44n
nXm UL MIMO

FIG.3B

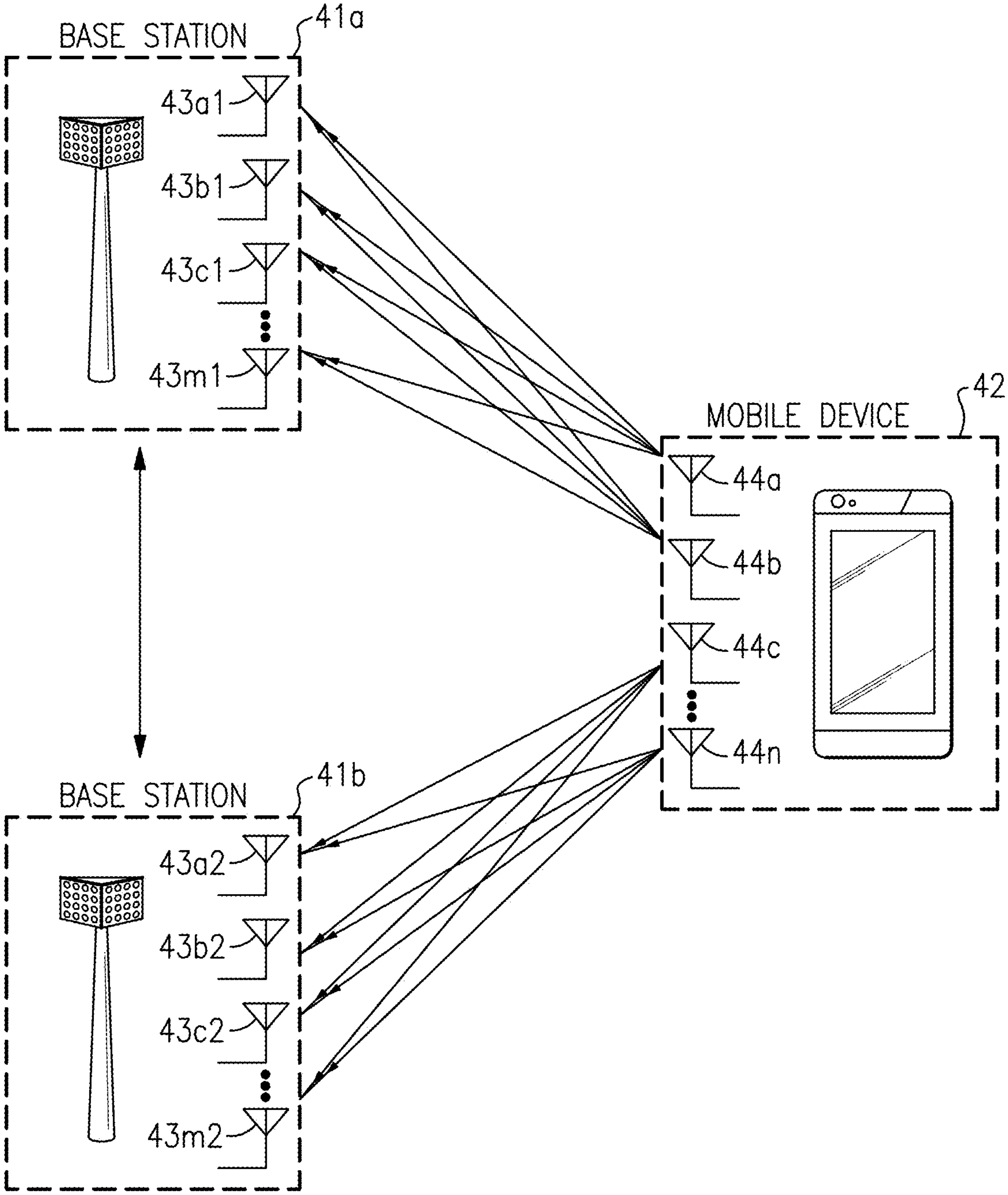

BASE STATION
41a
43a1
43b1
43c1
43m1
MOBILE DEVICE
42
44a
44b
44c
44n
BASE STATION
41b
43a2
43b2
43c2
43m2

FIG.3C

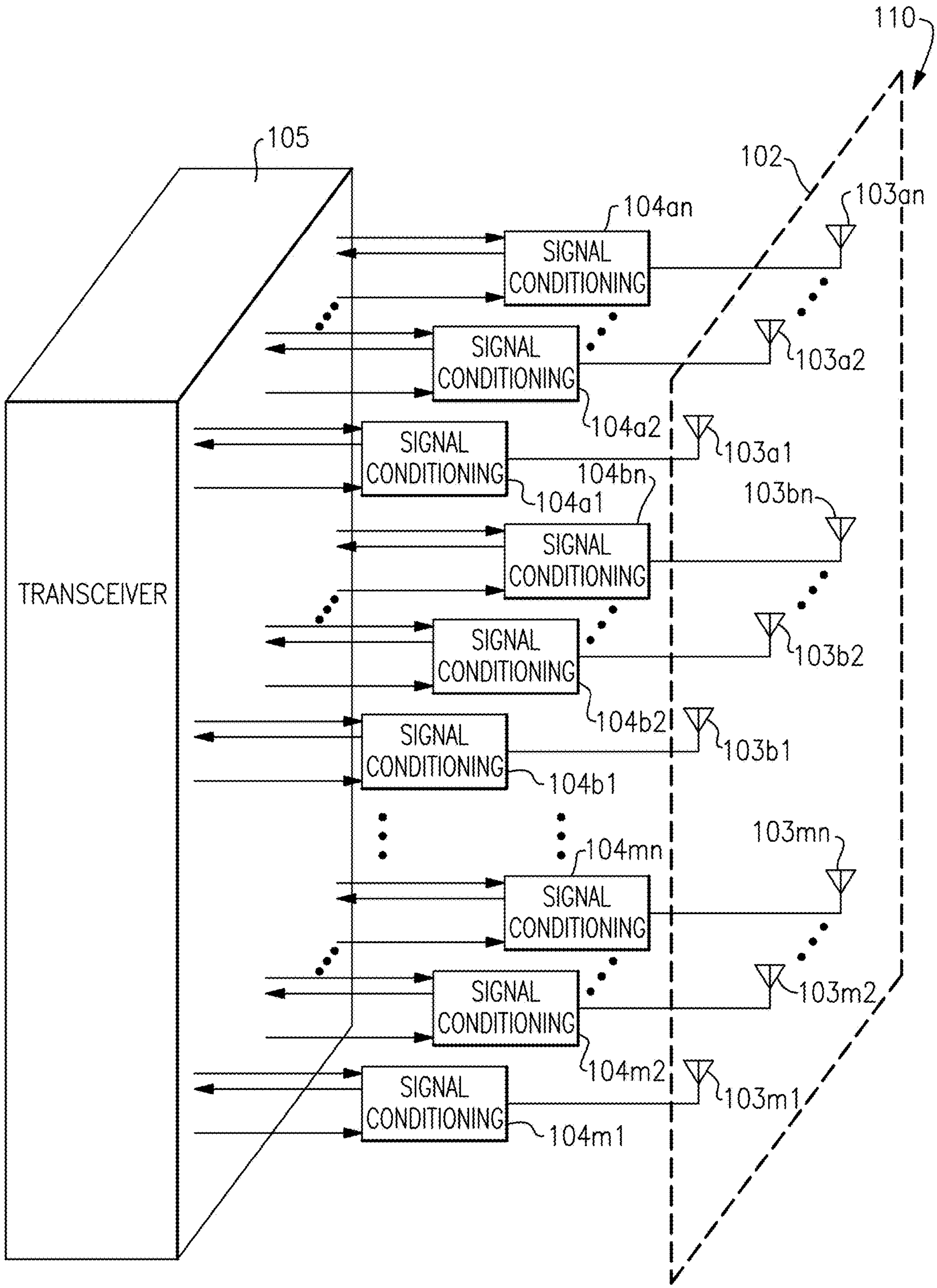

110
105
102
104an
103an
SIGNAL CONDITIONING
SIGNAL CONDITIONING
103a2
104a2
SIGNAL CONDITIONING
103a1
104bn
104a1
103bn
SIGNAL CONDITIONING
TRANSCEIVER
SIGNAL CONDITIONING
103b2
104b2
SIGNAL CONDITIONING
103b1
104b1
104mn
103mn
SIGNAL CONDITIONING
SIGNAL CONDITIONING
103m2
104m2
SIGNAL CONDITIONING
103m1
104m1

FIG.4A

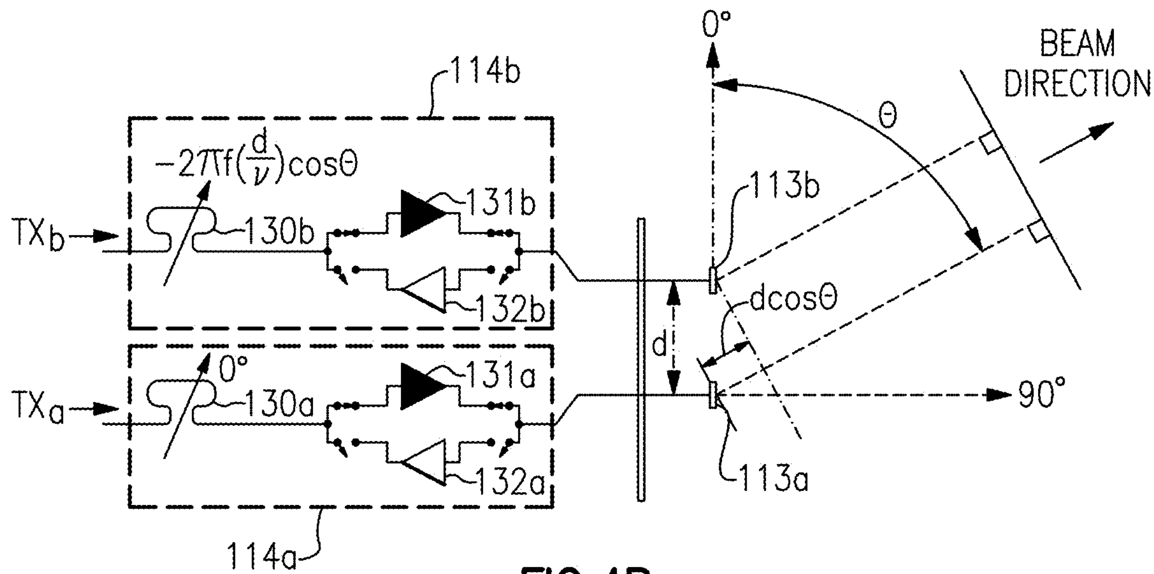

0°
BEAM
DIRECTION
114b
Θ
$-2\pi f(\frac{d}{\nu})\cos\Theta$
113b
TX_b
131b
130b
132b
dcosΘ
d
0°
131a
TX_a
130a
90°
132a
113a
114a

FIG.4B

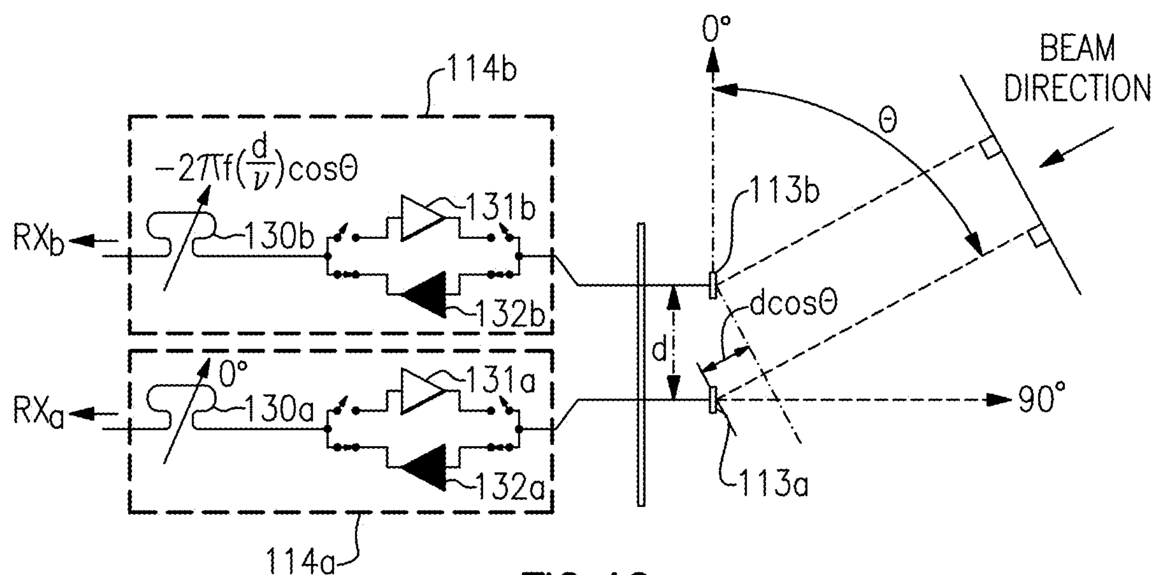

0°
BEAM
DIRECTION
114b
Θ
$-2\pi f(\frac{d}{\nu})\cos\Theta$
113b
RX_b
131b
130b
132b
dcosΘ
d
0°
131a
RX_a
130a
90°
132a
113a
114a

FIG.4C

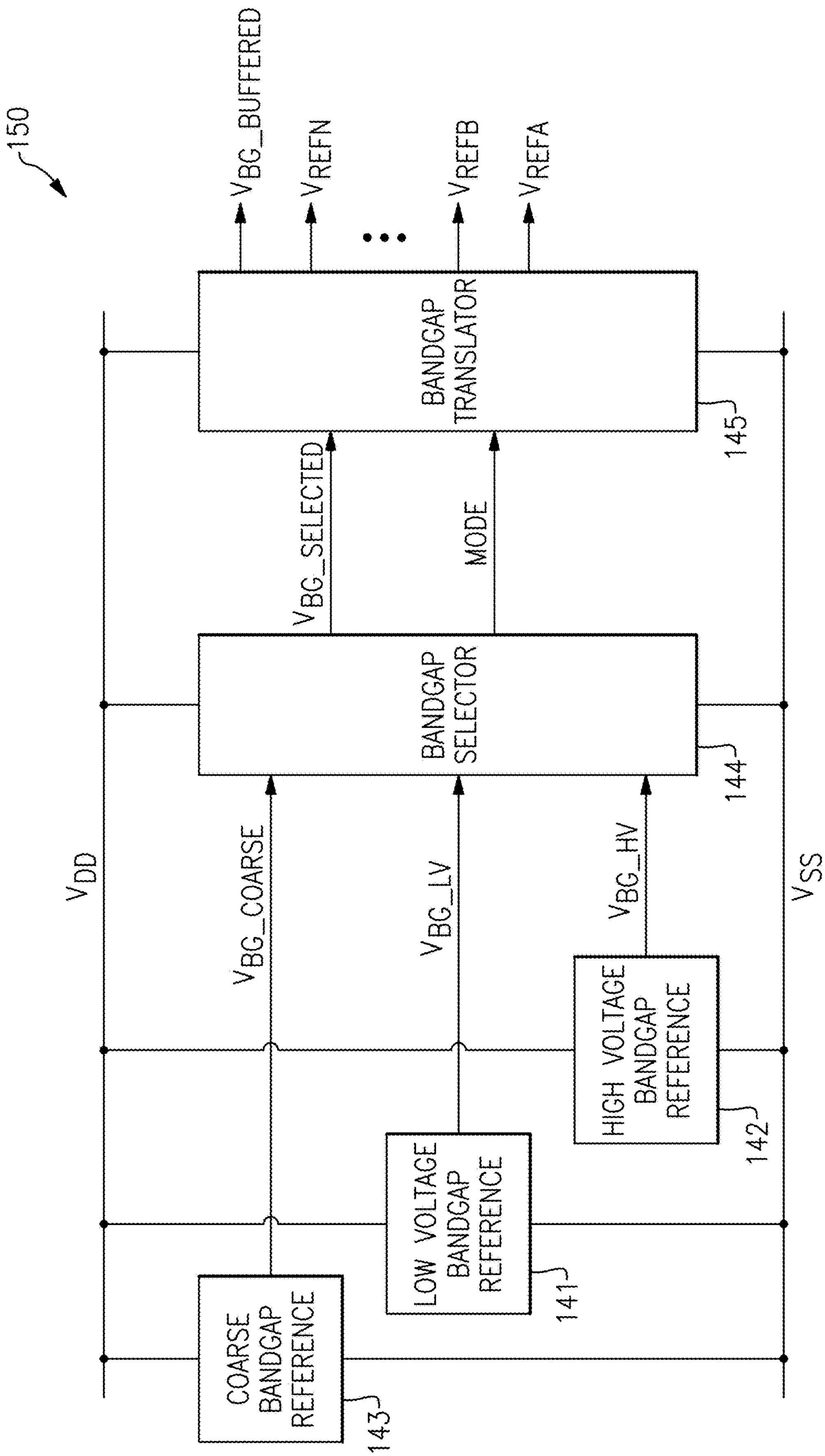

150
VBG_BUFFERED
VREFN
VREFB
VREFA
BANDGAP TRANSLATOR
145
VBG_SELECTED
MODE
BANDGAP SELECTOR
144
VDD
VBG_COARSE
VBG_LV
VBG_HV
VSS
HIGH VOLTAGE BANDGAP REFERENCE
142
LOW VOLTAGE BANDGAP REFERENCE
141
COARSE BANDGAP REFERENCE
143

FIG.5

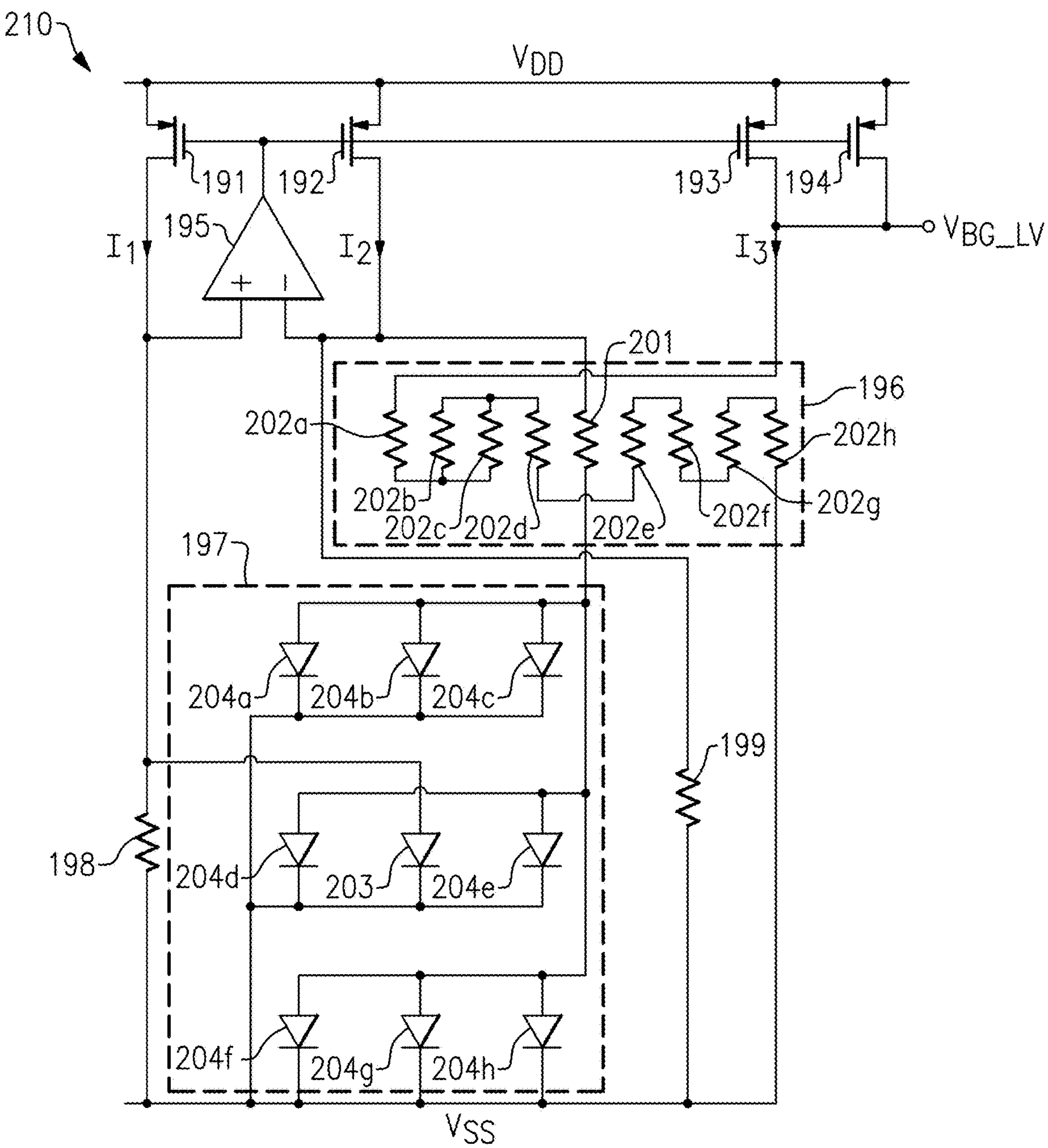

210
VDD
191
192
193
194
195
I1
I2
I3
VBG_LV
201
196
202a
202h
202b
202c
202d
202e
202f
202g
197
204a
204b
204c
199
198
204d
203
204e
204f
204g
204h
VSS

FIG.6A

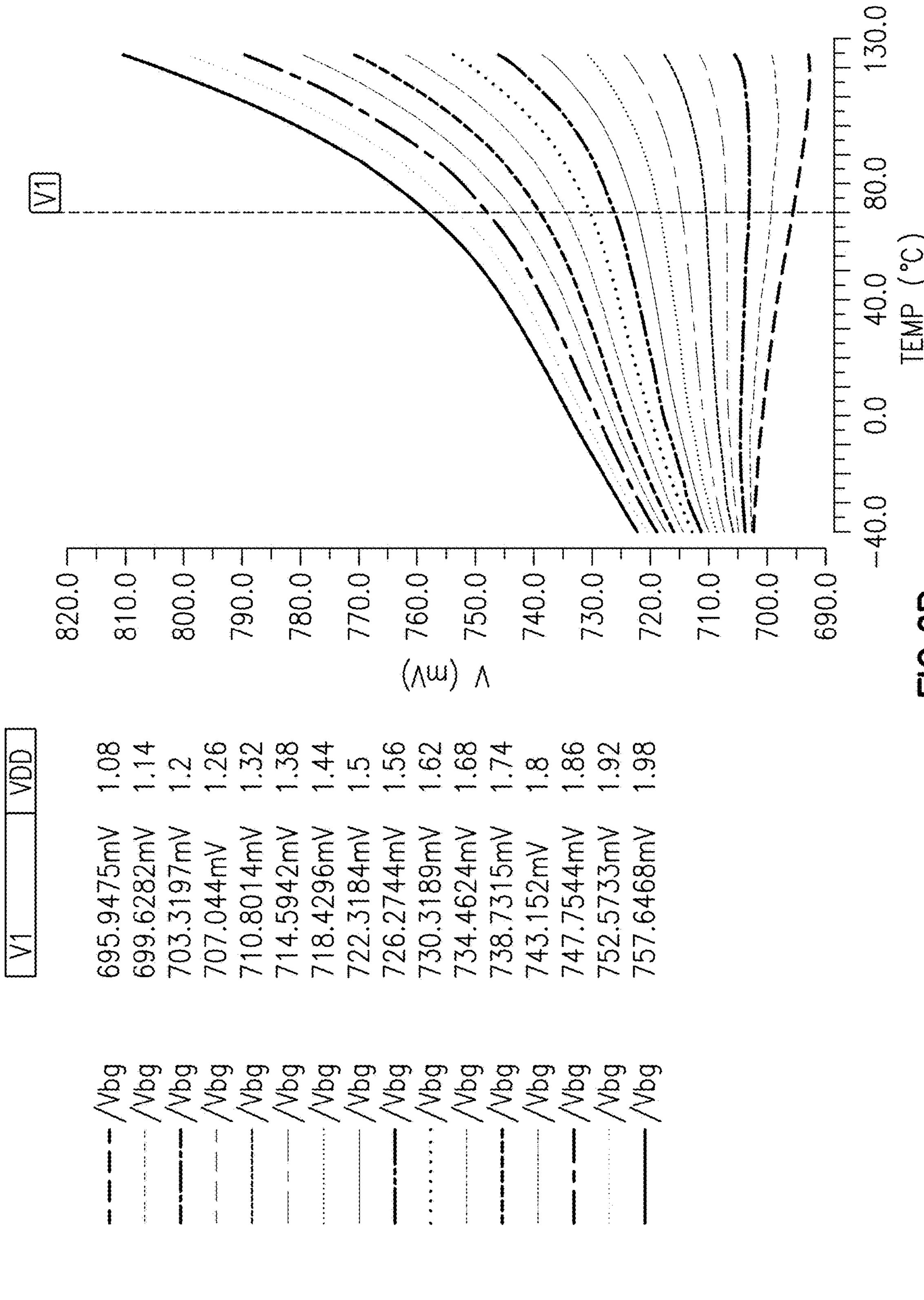

V1
VDD
/Vbg 695.9475mV 1.08
/Vbg 699.6282mV 1.14
/Vbg 703.3197mV 1.2
/Vbg 707.044mV 1.26
/Vbg 710.8014mV 1.32
/Vbg 714.5942mV 1.38
/Vbg 718.4296mV 1.44
/Vbg 722.3184mV 1.5
/Vbg 726.2744mV 1.56
/Vbg 730.3189mV 1.62
/Vbg 734.4624mV 1.68
/Vbg 738.7315mV 1.74
/Vbg 743.152mV 1.8
/Vbg 747.7544mV 1.86
/Vbg 752.5733mV 1.92
/Vbg 757.6468mV 1.98
V (mV)
820.0
810.0
800.0
790.0
780.0
770.0
760.0
750.0
740.0
730.0
720.0
710.0
700.0
690.0
V1
−40.0
0.0
40.0
80.0
130.0
TEMP (°C)

FIG.6B

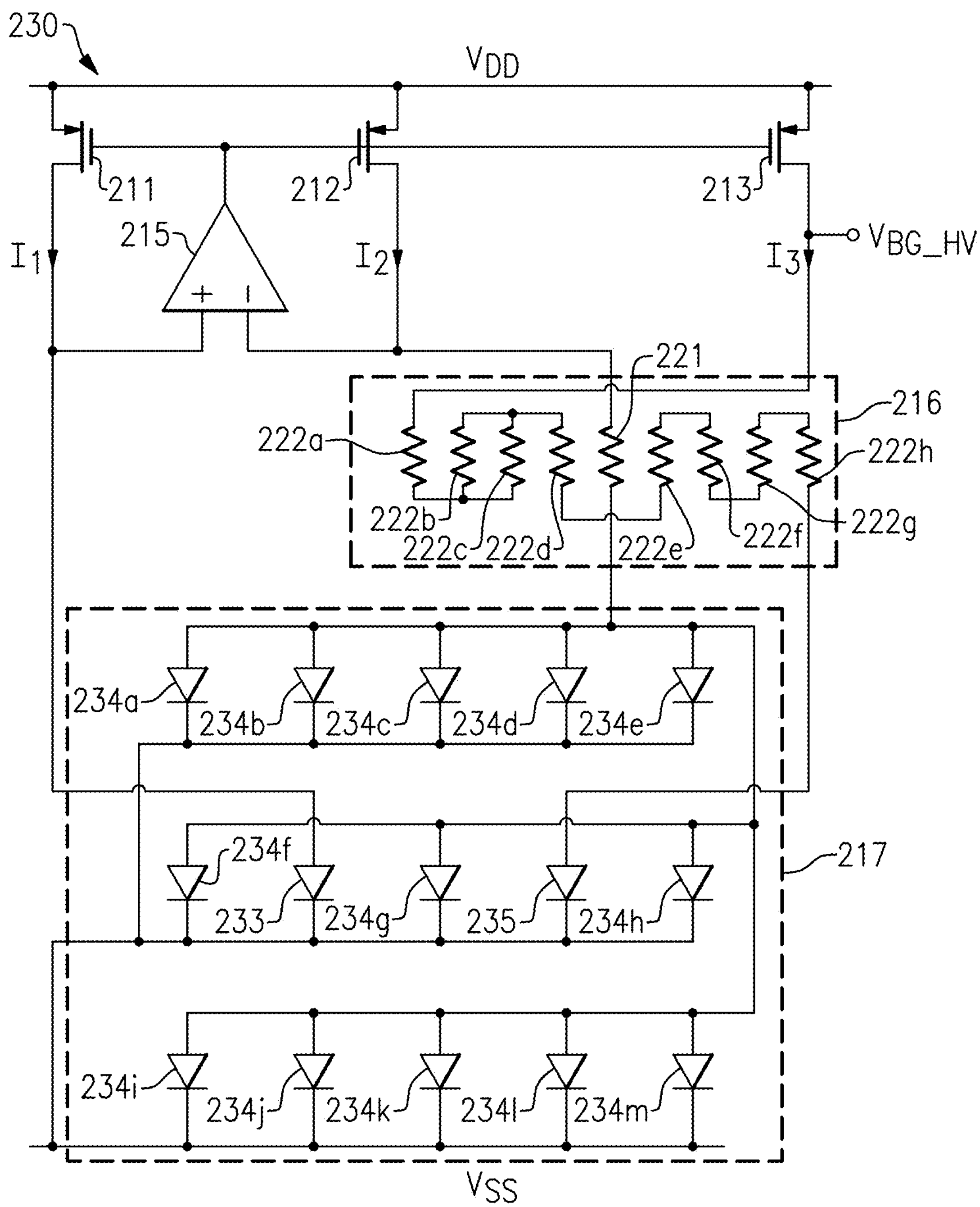

230
VDD
211
212
213
215
I1
I2
I3
VBG_HV
221
216
222a
222h
222b
222c
222d
222e
222f
222g
234a
234b
234c
234d
234e
234f
233
234g
235
234h
217
234i
234j
234k
234l
234m
VSS

FIG.7A

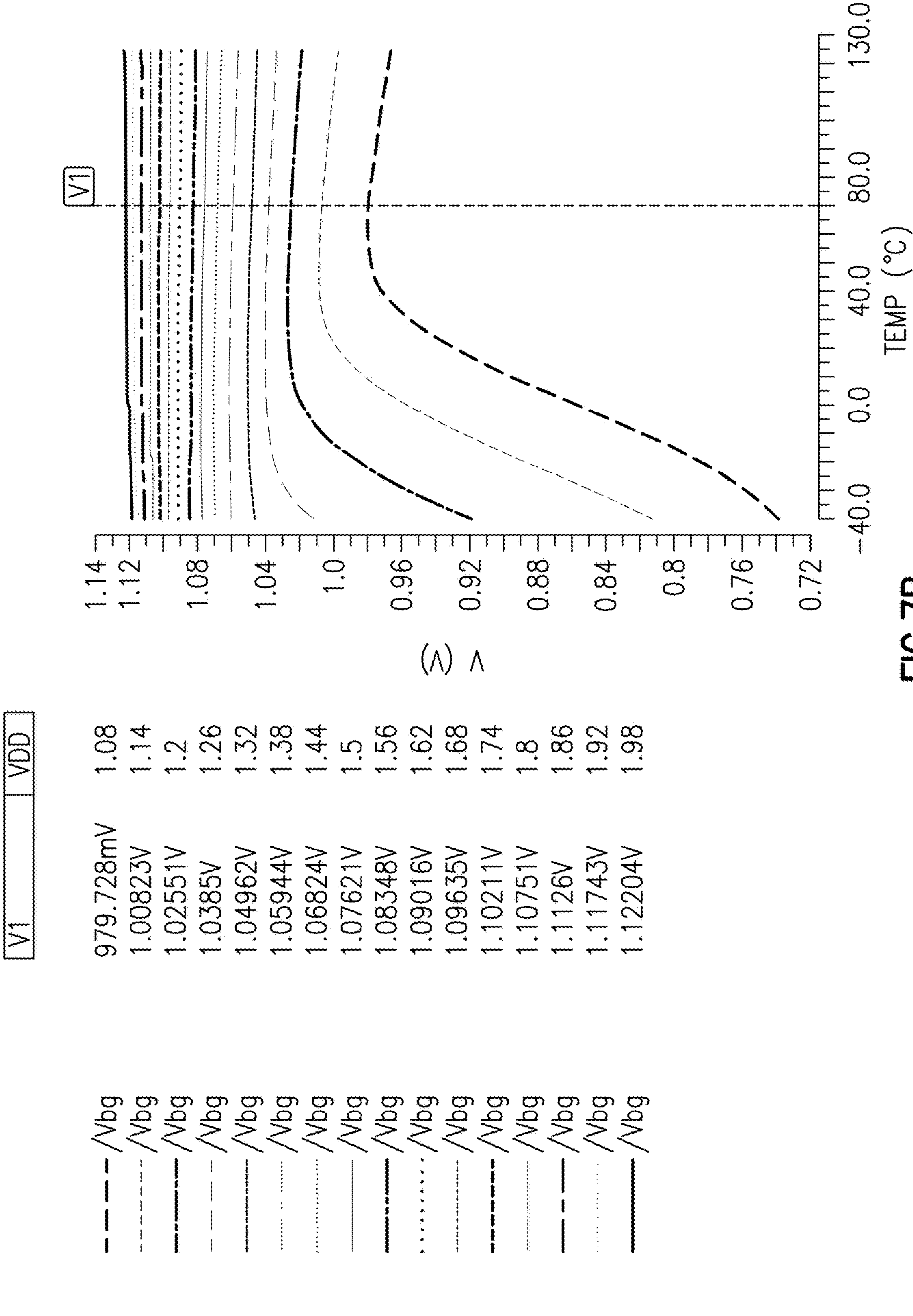

V1
TEMP (°C)
V (V)
1.14
1.12
1.08
1.04
1.0
0.96
0.92
0.88
0.84
0.8
0.76
0.72
−40.0
0.0
40.0
80.0
130.0
V1
VDD
979.728mV
1.08
1.00823V
1.14
1.02551V
1.2
1.0385V
1.26
1.04962V
1.32
1.05944V
1.38
1.06824V
1.44
1.07621V
1.5
1.08348V
1.56
1.09016V
1.62
1.09635V
1.68
1.10211V
1.74
1.10751V
1.8
1.1126V
1.86
1.11743V
1.92
1.12204V
1.98
/Vbg
/Vbg
/Vbg
/Vbg
/Vbg
/Vbg
/Vbg
/Vbg
/Vbg
/Vbg
/Vbg
/Vbg
/Vbg
/Vbg
/Vbg
/Vbg

FIG.7B

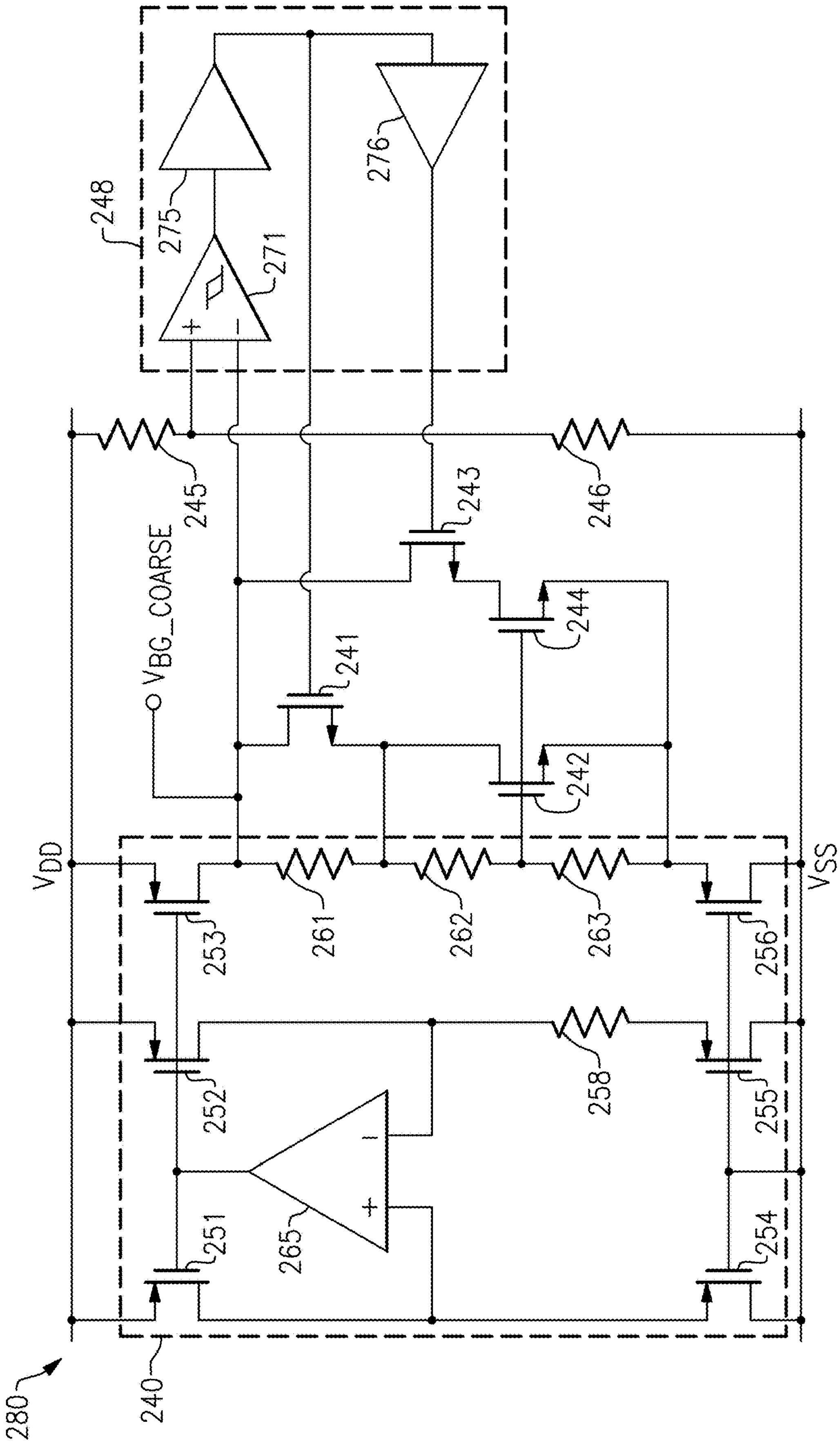

248
275
271
276
245
243
246
V_{BG_COARSE}
244
241
242
V_{DD}
V_{SS}
253
261
262
263
256
252
258
255
265
251
254
280
240

FIG.8A

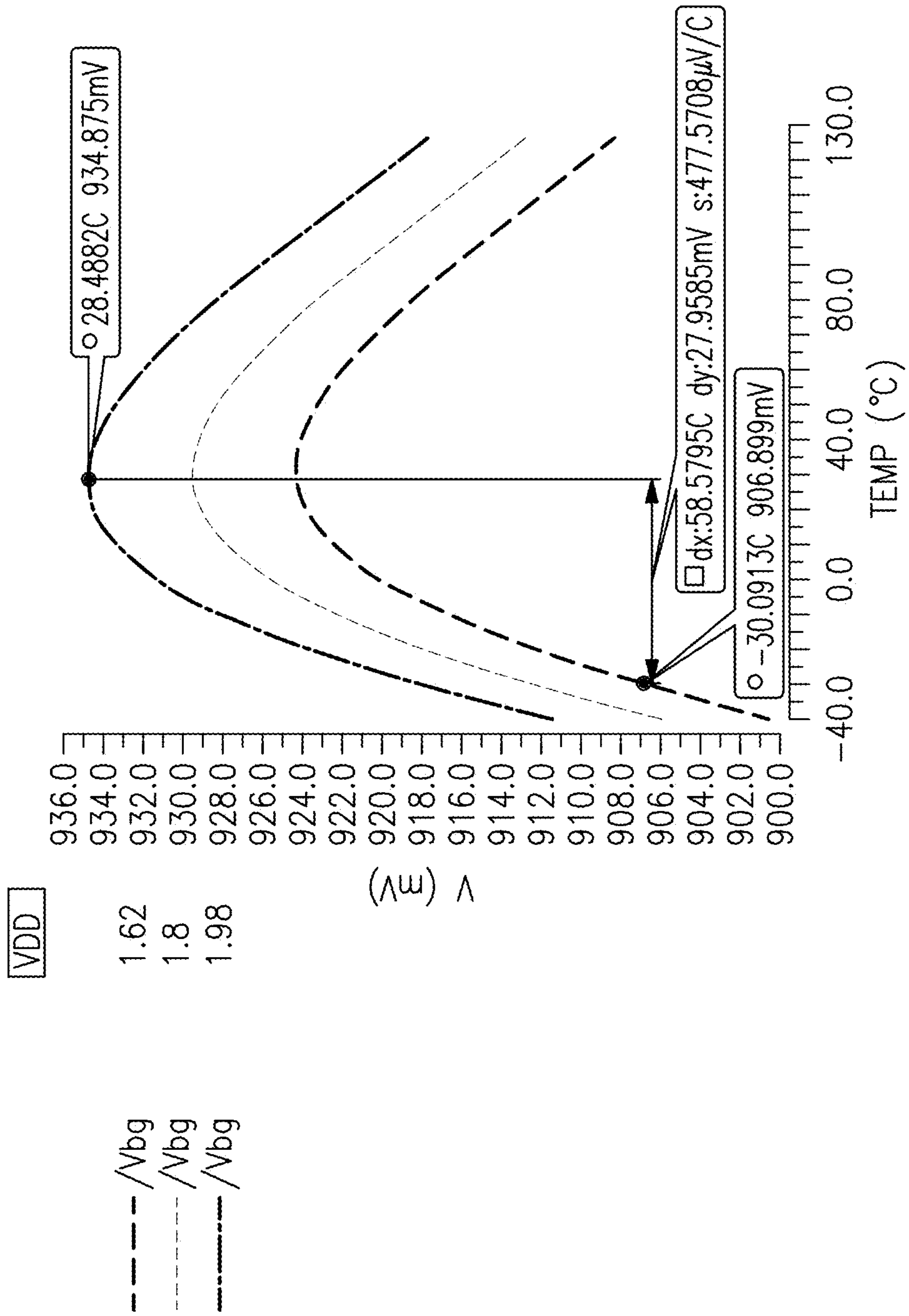
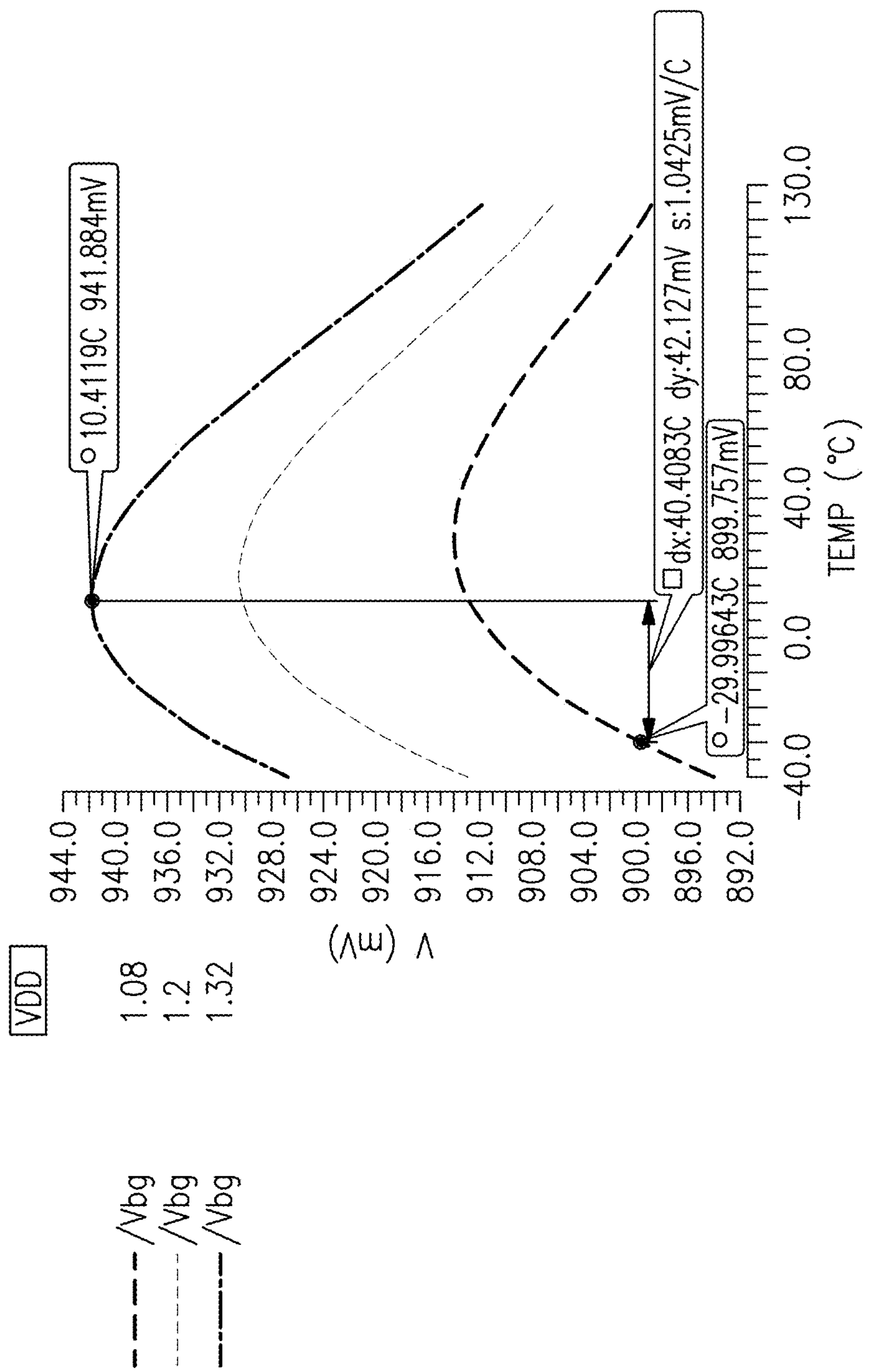

28.4882C 934.875mV
dx:58.5795C dy:27.9585mV s:477.5708μV/C
−30.0913C 906.899mV
VDD
1.62
1.8
1.98
/Vbg
/Vbg
/Vbg
V (mV)
936.0
934.0
932.0
930.0
928.0
926.0
924.0
922.0
920.0
918.0
916.0
914.0
912.0
910.0
908.0
906.0
904.0
902.0
900.0
−40.0
0.0
40.0
80.0
130.0
TEMP (°C)

FIG.8B



VDD
1.08
1.2
1.32
/Vbg
/Vbg
/Vbg
V (mV)
944.0
940.0
936.0
932.0
928.0
924.0
920.0
916.0
912.0
908.0
904.0
900.0
896.0
892.0
−40.0
0.0
40.0
80.0
130.0
TEMP (°C)
10.4119C 941.884mV
−29.99643C 899.757mV
dx:40.4083C dy:42.127mV s:1.0425mV/C

FIG.8C

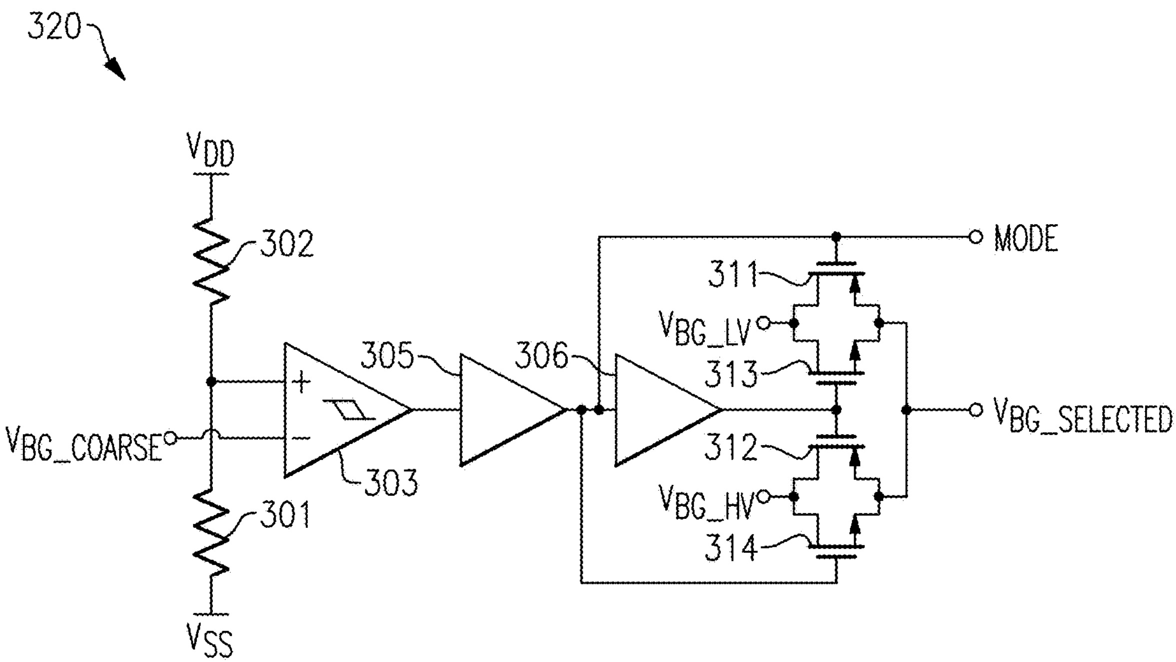

320
VDD
302
VBG_COARSE
+
−
305
306
303
301
VSS
MODE
311
VBG_LV
313
VBG_SELECTED
312
VBG_HV
314

FIG.9

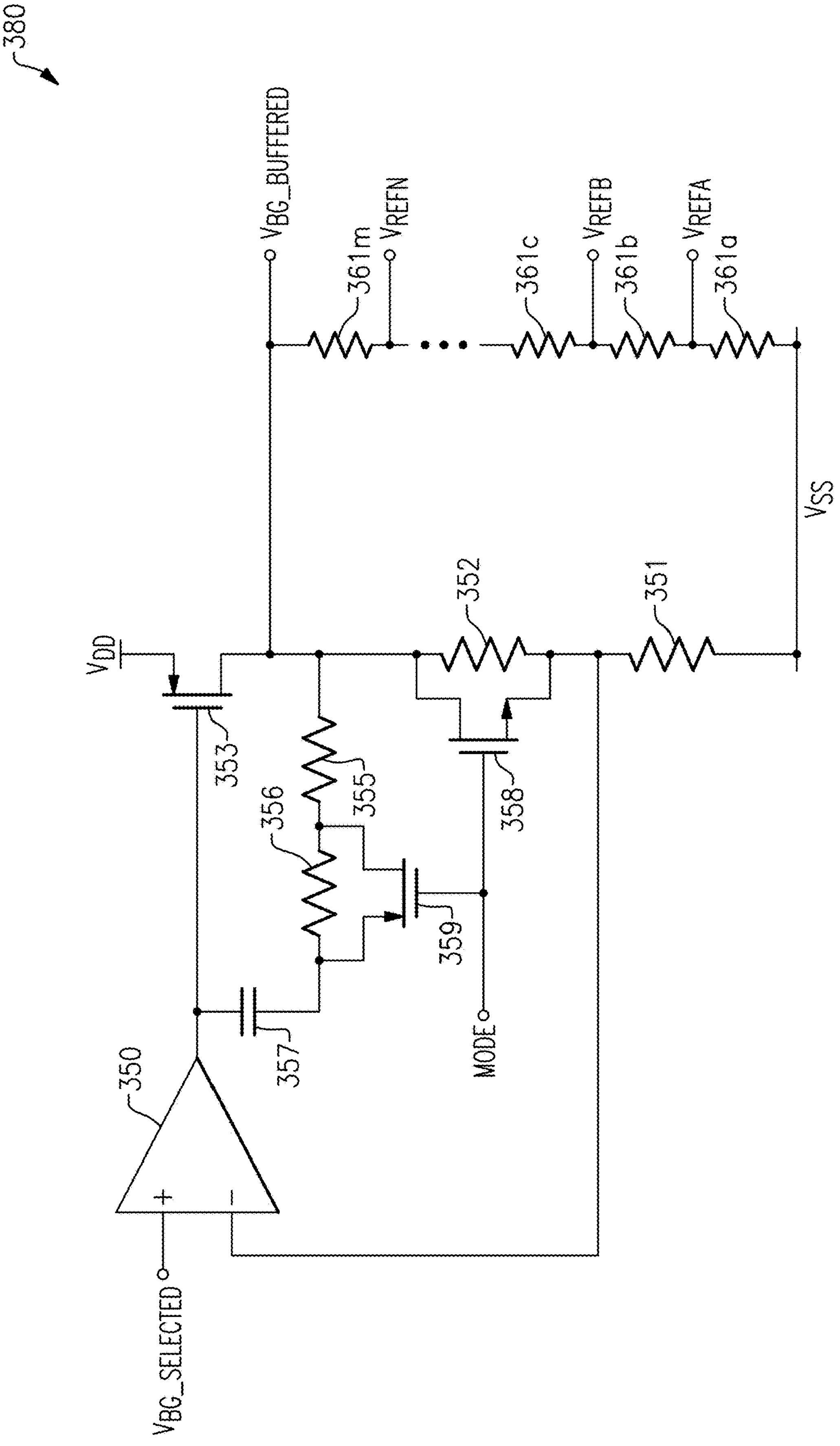

380
VBG_BUFFERED
VREFN
VREFB
VREFA
361m
361c
361b
361a
VSS
VDD
352
351
353
355
356
358
359
357
350
MODE
VBG_SELECTED

FIG. 10A

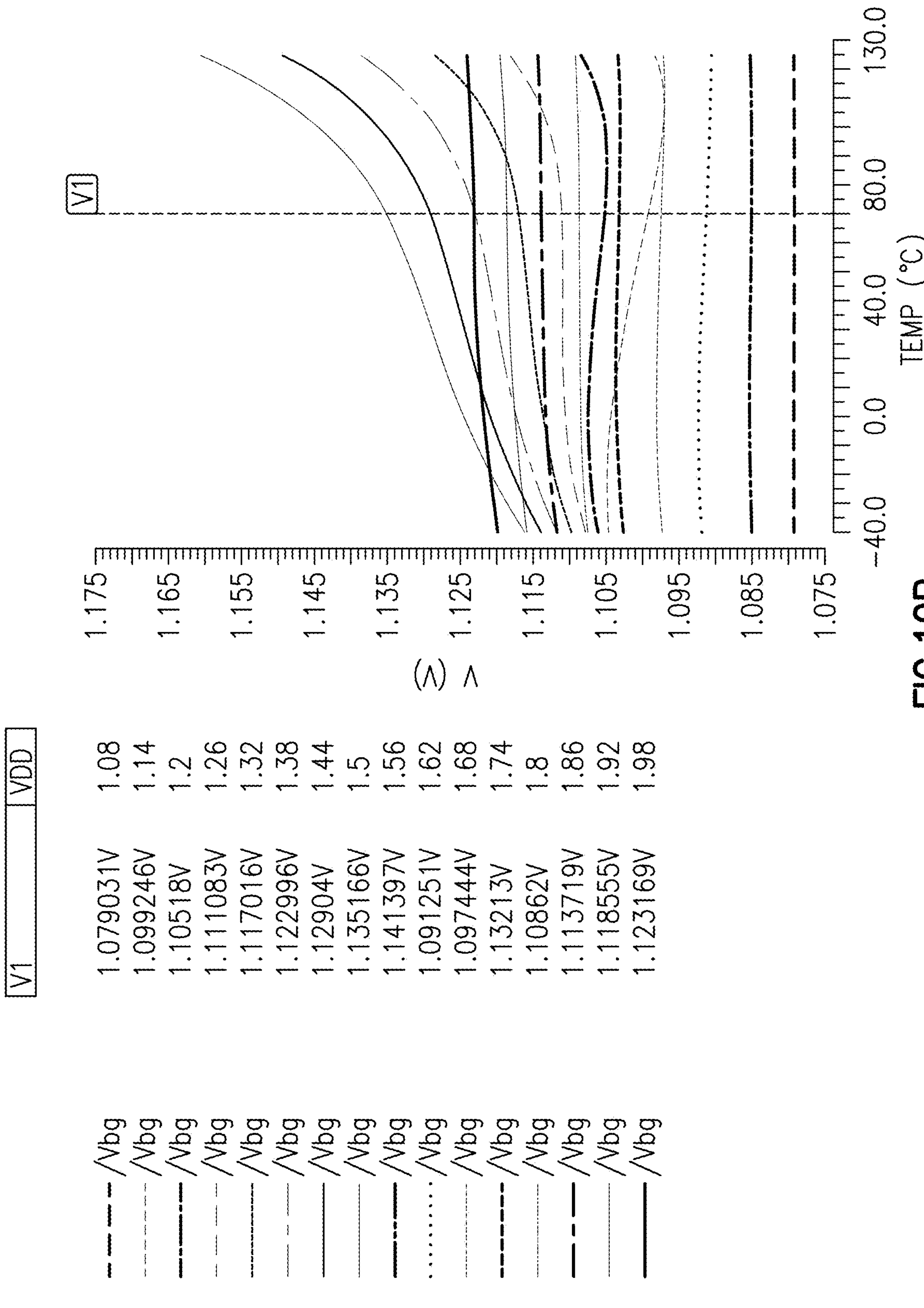

V1
VDD
/Vbg 1.079031V 1.08
/Vbg 1.099246V 1.14
/Vbg 1.10518V 1.2
/Vbg 1.111083V 1.26
/Vbg 1.117016V 1.32
/Vbg 1.122996V 1.38
/Vbg 1.12904V 1.44
/Vbg 1.135166V 1.5
/Vbg 1.141397V 1.56
/Vbg 1.091251V 1.62
/Vbg 1.097444V 1.68
/Vbg 1.13213V 1.74
/Vbg 1.10862V 1.8
/Vbg 1.113719V 1.86
/Vbg 1.118555V 1.92
/Vbg 1.123169V 1.98
V (V)
1.175
1.165
1.155
1.145
1.135
1.125
1.115
1.105
1.095
1.085
1.075
V1
TEMP (°C)
−40.0
0.0
40.0
80.0
130.0

FIG.10B

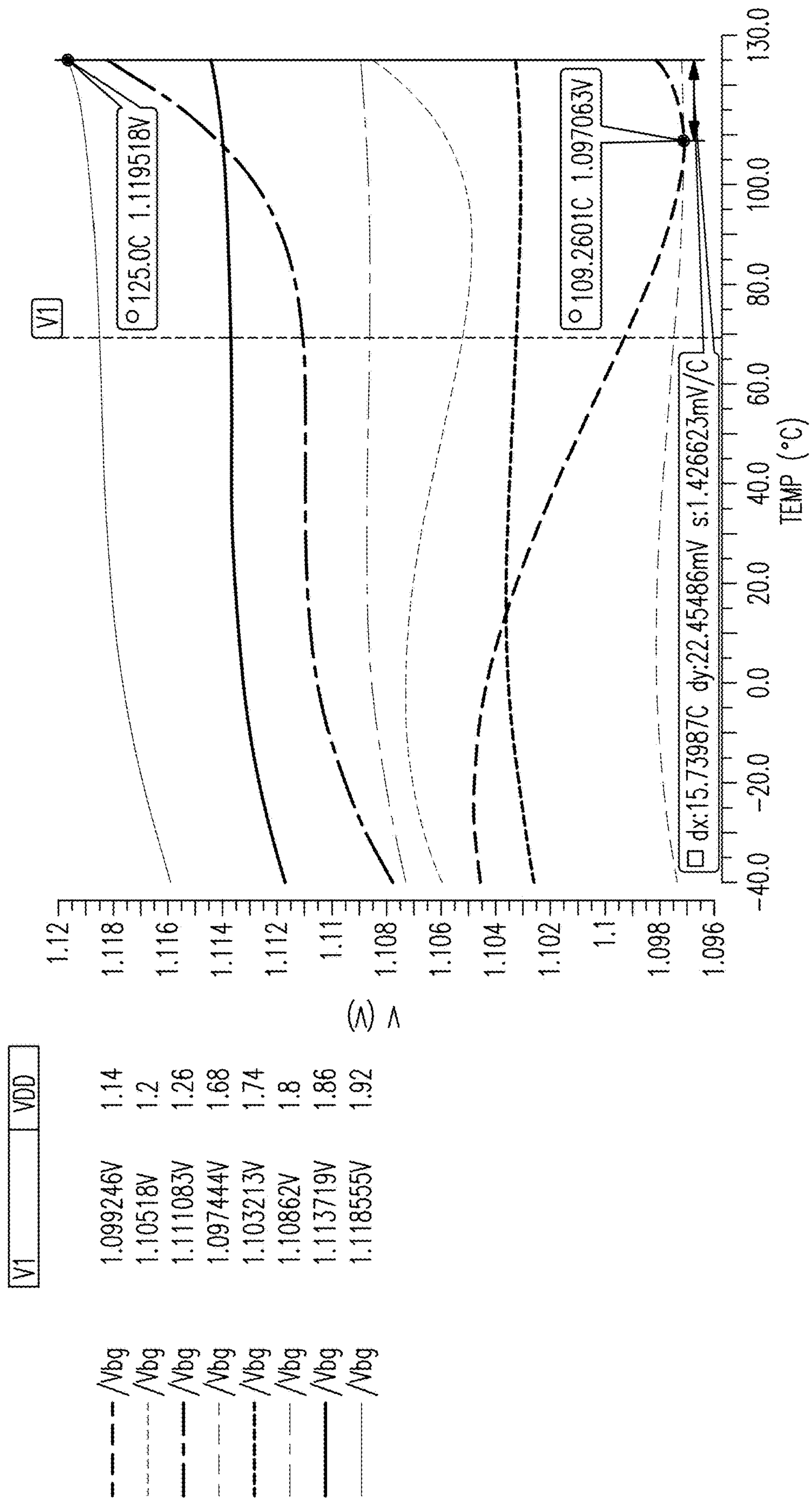

/Vbg
/Vbg
/Vbg
/Vbg
/Vbg
/Vbg
/Vbg
/Vbg
V1
VDD
1.099246V 1.14
1.10518V 1.2
1.111083V 1.26
1.097444V 1.68
1.103213V 1.74
1.10862V 1.8
1.113719V 1.86
1.118555V 1.92
V (V)
1.12
1.118
1.116
1.114
1.112
1.11
1.108
1.106
1.104
1.102
1.1
1.098
1.096
V1
125.0C 1.119518V
109.2601C 1.097063V
dx:15.73987C dy:22.45486mV s:1.426623mV/C
−40.0
−20.0
0.0
20.0
40.0
60.0
80.0
100.0
130.0
TEMP (°C)

FIG.10C

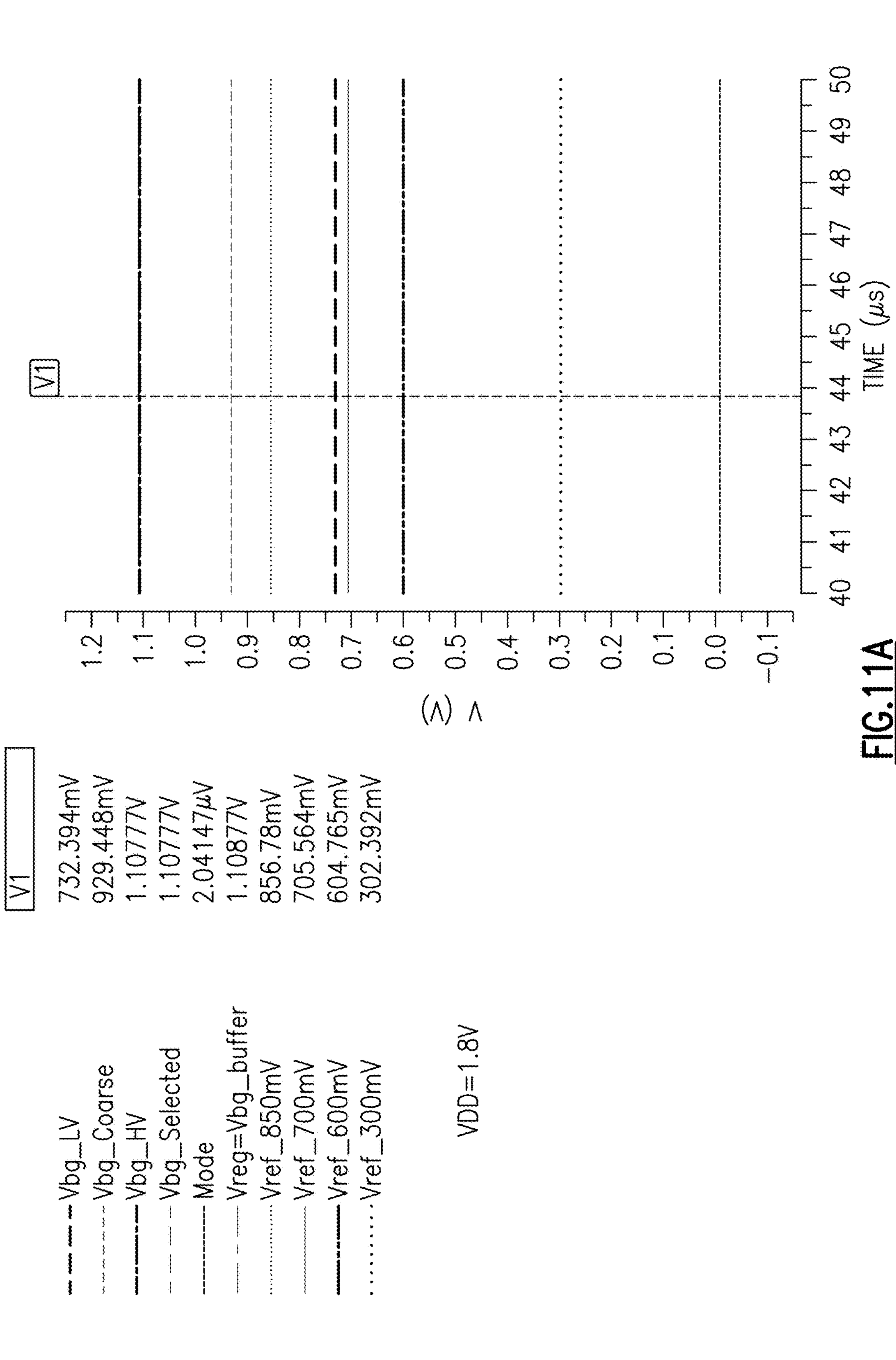

V1
Vbg_LV
Vbg_Coarse
Vbg_HV
Vbg_Selected
Mode
Vreg=Vbg_buffer
Vref_850mV
Vref_700mV
Vref_600mV
Vref_300mV
732.394mV
929.448mV
1.10777V
1.10777V
2.04147µV
1.10877V
856.78mV
705.564mV
604.765mV
302.392mV
VDD=1.8V
V (V)
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
40
41
42
43
44
45
46
47
48
49
50
TIME (µs)

FIG.11A

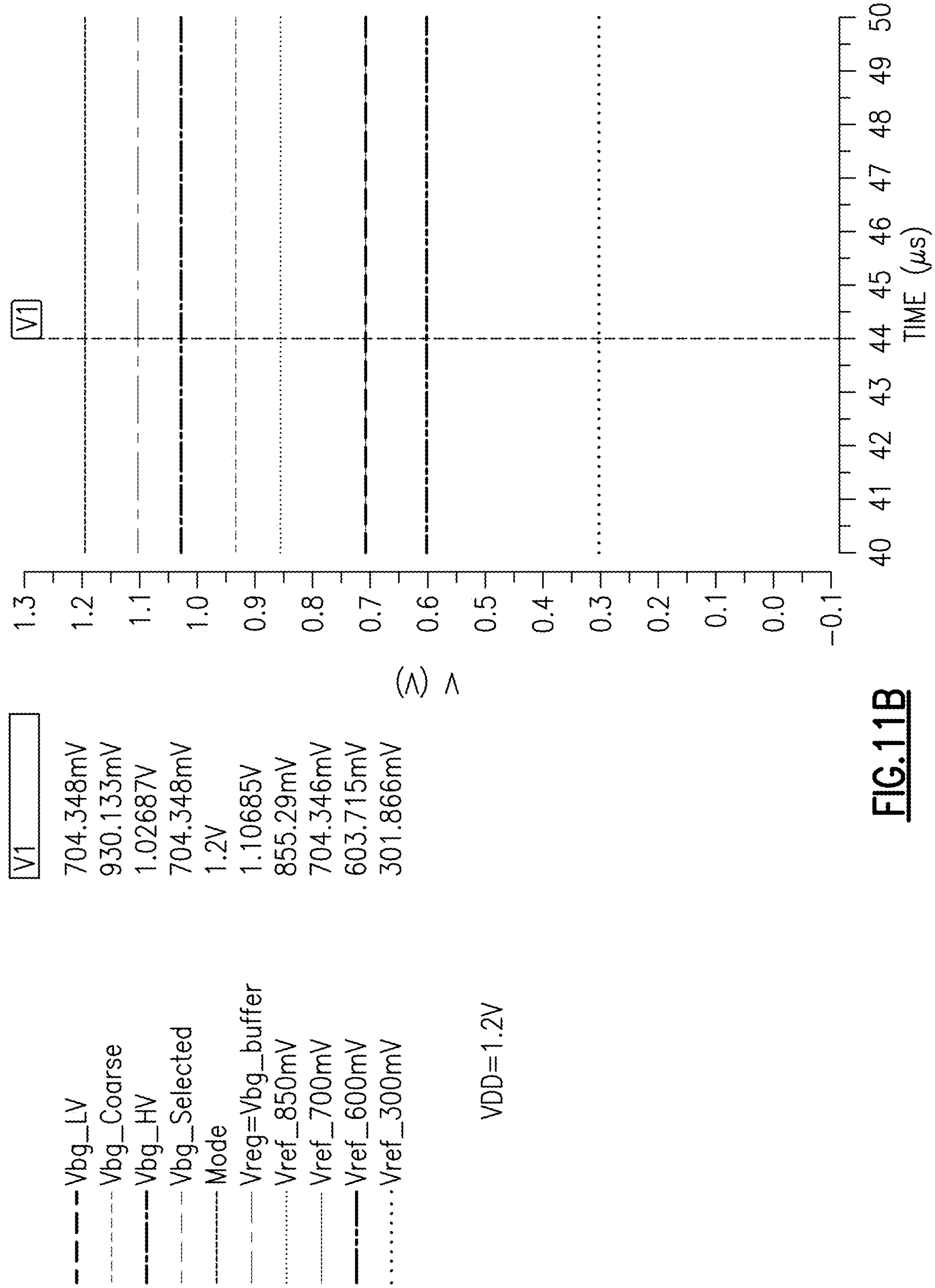

Vbg_LV
Vbg_Coarse
Vbg_HV
Vbg_Selected
Mode
Vreg=Vbg_buffer
Vref_850mV
Vref_700mV
Vref_600mV
Vref_300mV
V1
704.348mV
930.133mV
1.02687V
704.348mV
1.2V
1.10685V
855.29mV
704.346mV
603.715mV
301.866mV
VDD=1.2V
V (V)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
V1
40
41
42
43
44
45
46
47
48
49
50
TIME (μs)

FIG.11B

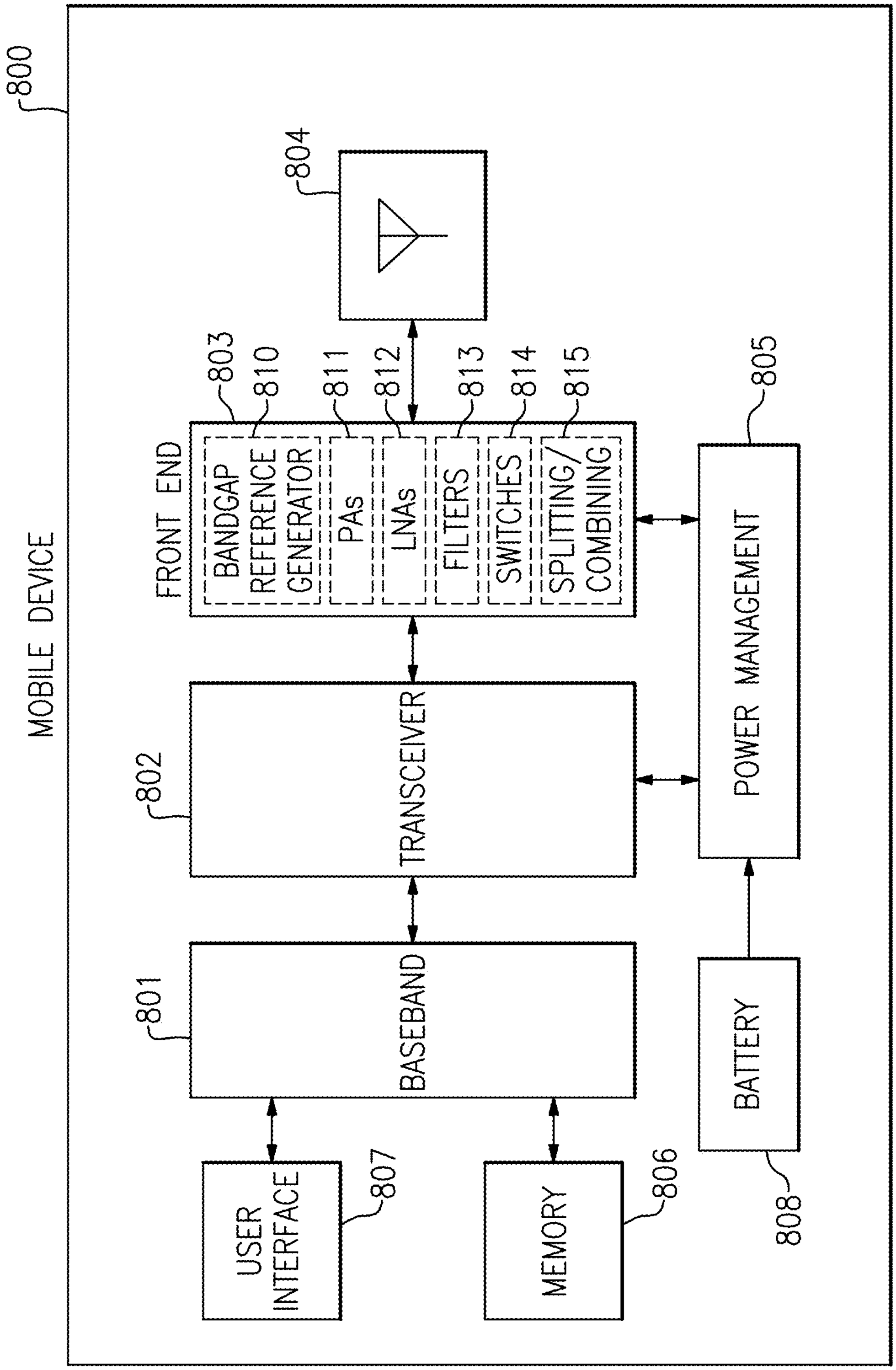

800
MOBILE DEVICE
804
803
810
811
812
813
814
815
FRONT END
BANDGAP REFERENCE GENERATOR
PAs
LNAs
FILTERS
SWITCHES
SPLITTING/ COMBINING
805
POWER MANAGEMENT
802
TRANSCEIVER
801
BASEBAND
BATTERY
808
USER INTERFACE
807
MEMORY
806

FIG.12

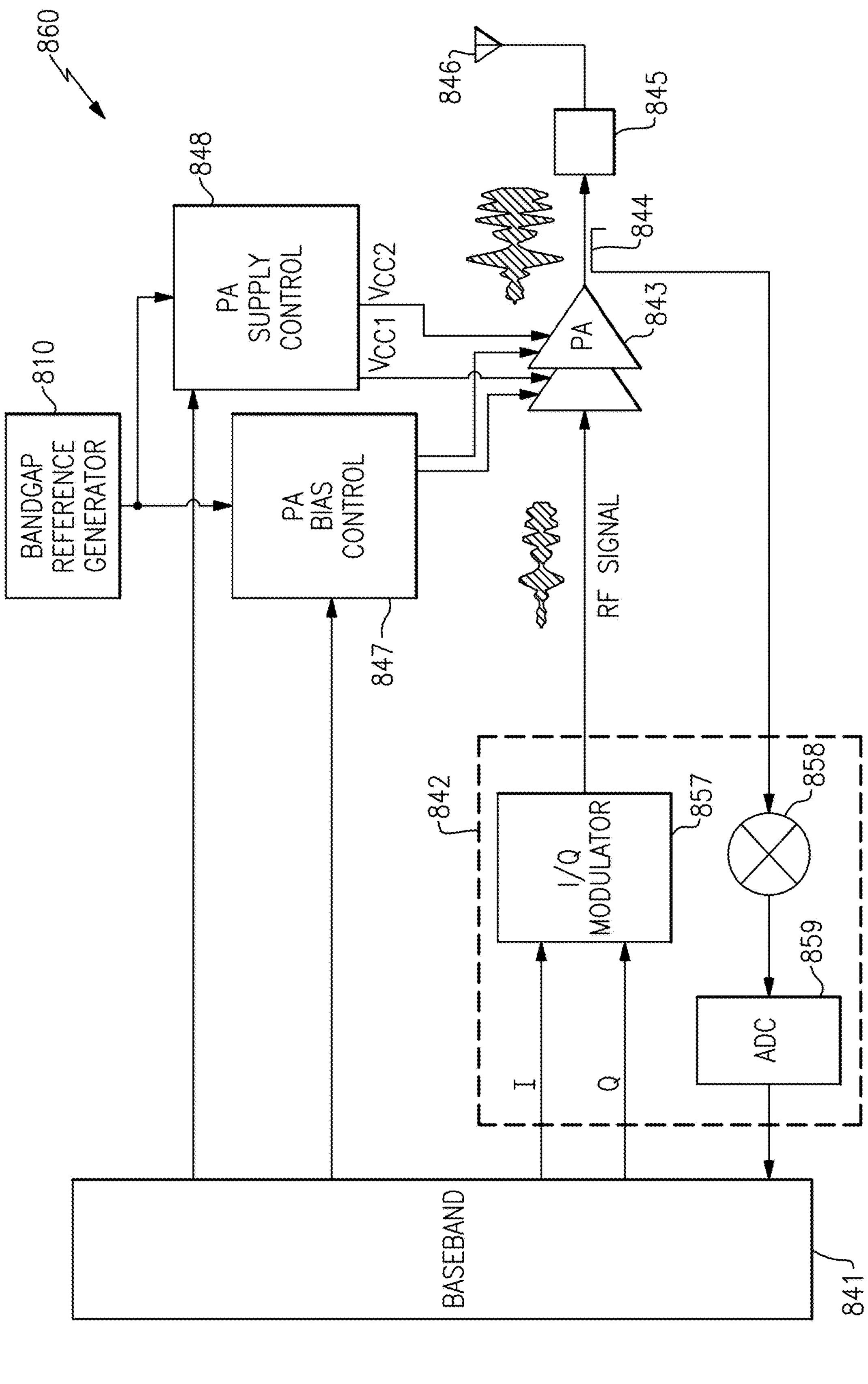

860
810
BANDGAP REFERENCE GENERATOR
848
PA SUPPLY CONTROL
VCC1
VCC2
PA BIAS CONTROL
847
846
845
844
PA
843
RF SIGNAL
842
I/Q MODULATOR
857
858
859
ADC
I
Q
BASEBAND
841

FIG.13

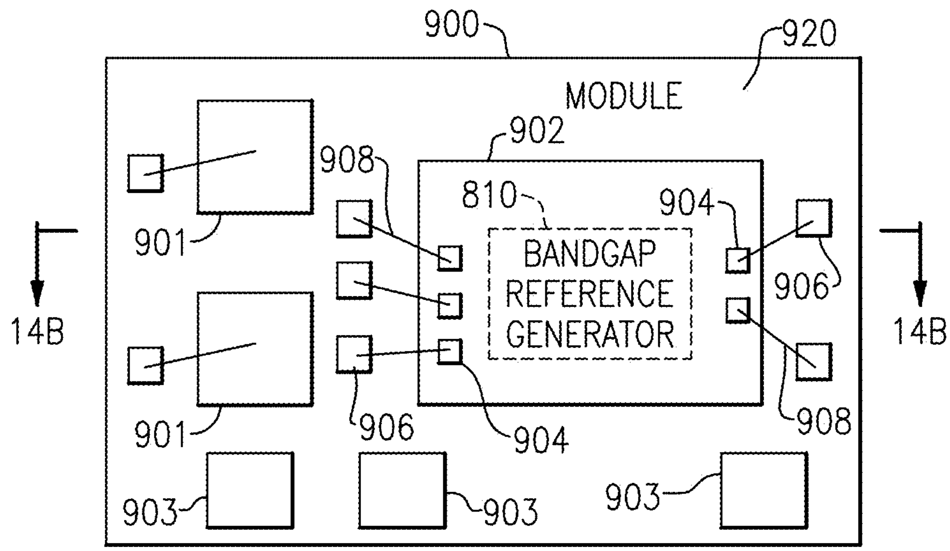


FIG.14A

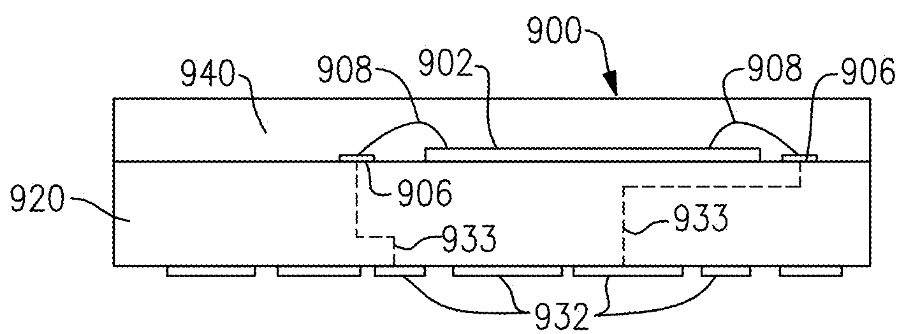


FIG.14B

BANDGAP REFERENCE GENERATION FOR MULTIPLE POWER SUPPLY DOMAINS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of U.S. patent application Ser. No. 18/332,208, filed Jun. 9, 2023 and titled "BANDGAP REFERENCE GENERATION FOR MULTIPLE POWER SUPPLY DOMAINS," which claims the benefit of priority under 35 U.S.C. § 119 of U.S. Provisional Patent Application No. 63/366,706, filed Jun. 21, 2022 and titled "BANDGAP REFERENCE GENERATION FOR MULTIPLE POWER SUPPLY DOMAINS," each of which is herein incorporated by reference in its entirety.

BACKGROUND

Technical Field

[0002] Embodiments of the invention relate to electronic systems, and in particular, to radio frequency (RF) electronics.

Description of Related Technology

[0003] A communication system can include a transceiver, a front end, and one or more antennas for wirelessly transmitting and/or receiving signals. The front end can include low noise amplifier(s) for amplifying relatively weak signals received via the antenna(s), and power amplifier(s) for boosting signals for transmission via the antenna(s).

[0004] Examples of communication systems include, but are not limited to, mobile phones, tablets, base stations, network access points, customer-premises equipment (CPE), laptops, and wearable electronics.

SUMMARY

[0005] In certain embodiments, the present disclosure relates to a bandgap reference generator. The bandgap reference generator includes a low voltage bandgap reference circuit configured to generate a first bandgap reference voltage over a first range of a power supply voltage, a high voltage bandgap reference circuit configured to generate a second bandgap reference voltage over a second range of the power supply voltage that is greater than the first range, a bandgap selector circuit configured to output a selected bandgap reference voltage by selecting the first bandgap reference voltage or the second bandgap reference voltage based on a voltage level of the power supply voltage, and a bandgap translator circuit configured to generate a buffered bandgap reference voltage based on the selected bandgap reference voltage.

[0006] In some embodiments, the bandgap reference generator further includes a coarse bandgap reference circuit configured to generate a third bandgap reference voltage, the bandgap selector circuit further configured to compare the voltage level of the power supply voltage to the third bandgap reference voltage. According to a number of embodiments, the coarse bandgap reference circuit operates over a third range of the power supply voltage that includes the first range and the second range. In accordance with several embodiments, the third bandgap reference voltage is of a lower precision than the first bandgap reference voltage and the second bandgap reference voltage.

[0007] In various embodiments, the bandgap translator circuit is further configured to output a plurality of reference voltages by scaling the buffered bandgap reference voltage by a plurality of different scaling factors.

[0008] In some embodiments, the bandgap translator circuit is further configured to generate the buffered bandgap reference voltage to compensate for a nominal voltage difference between the first bandgap reference voltage and the second bandgap reference voltage.

[0009] In several embodiments, the bandgap selector circuit is further configured to provide the bandgap translator circuit with a mode signal indicating the selected bandgap reference voltage. According to a number of embodiments, the bandgap translator circuit includes a differential amplifier operable to control a transistor by way of a feedback loop, the mode signal operable to control an impedance of a compensation circuit to maintain stability of the feedback loop. In accordance with various embodiments, the bandgap translator circuit is configured to operate as a low dropout regulator in a first state of the mode signal, and to operate as a unity gain buffer in a second state of the mode signal.

[0010] In several embodiments, the bandgap reference generator is implemented in a front end module.

[0011] In certain embodiments, the present disclosure relates to a method of bandgap voltage generation. The method includes generating a first bandgap reference voltage over a first range of a power supply voltage using a low voltage bandgap reference circuit and generating a second bandgap reference voltage over a second range of the power supply voltage using a high voltage bandgap reference circuit, the second range greater than the first range. The method further includes outputting a selected bandgap reference voltage by selecting the first bandgap reference voltage or the second bandgap reference voltage based on a voltage level of the power supply voltage using a bandgap selector circuit, and generating a buffered bandgap reference voltage based on the selected bandgap reference voltage using a bandgap translator circuit.

[0012] In some embodiments, the method further includes generating a third bandgap reference voltage using a coarse bandgap reference circuit, and comparing the voltage level of the power supply voltage to the third bandgap reference voltage using the bandgap selector circuit. According to a number of embodiments, the coarse bandgap reference circuit operates over a third range of the power supply voltage that includes the first range and the second range. In accordance with several embodiments, the third bandgap reference voltage is of a lower precision than the first bandgap reference voltage and the second bandgap reference voltage.

[0013] In various embodiments, the method further includes scaling the buffered bandgap reference voltage to generate a plurality of reference voltages using the bandgap translator circuit.

[0014] In several embodiments, the method further includes compensating the buffered bandgap reference voltage for a nominal voltage difference between the first bandgap reference voltage and the second bandgap reference voltage using the bandgap translator circuit.

[0015] In some embodiments, the method further includes generating a mode signal indicating the selected bandgap reference voltage using the bandgap selector circuit, and providing the mode signal to the bandgap translator circuit. According to a number of embodiments, the method further includes processing the mode signal to maintain stability of a feedback loop of the bandgap translator circuit. In accordance with several embodiments, the method further includes operating the bandgap translator circuit as a low dropout regulator in a first state of the mode signal, and as a unity gain buffer in a second state of the mode signal.

[0016] In certain embodiments, the present disclosure relates to a front end module. The front end module includes a package substrate, and a semiconductor die attached to the package substrate. The semiconductor die includes a low voltage bandgap reference circuit configured to generate a first bandgap reference voltage over a first range of a power supply voltage, a high voltage bandgap reference circuit configured to generate a second bandgap reference voltage over a second range of the power supply voltage that is greater than the first range, a bandgap selector circuit configured to output a selected bandgap reference voltage by selecting the first bandgap reference voltage or the second bandgap reference voltage based on a voltage level of the power supply voltage, and a bandgap translator circuit configured to generate a buffered bandgap reference voltage based on the selected bandgap reference voltage.

[0017] In various embodiments, the semiconductor die further includes a coarse bandgap reference circuit configured to generate a third bandgap reference voltage, the bandgap selector circuit further configured to compare the voltage level of the power supply voltage to the third bandgap reference voltage. According to a number of embodiments, the coarse bandgap reference circuit operates over a third range of the power supply voltage that includes the first range and the second range. In accordance with several embodiments, the third bandgap reference voltage is of a lower precision than the first bandgap reference voltage and the second bandgap reference voltage.

[0018] In some embodiments, the bandgap translator circuit is further configured to output a plurality of reference voltages by scaling the buffered bandgap reference voltage by a plurality of different scaling factors.

[0019] In several embodiments, the bandgap translator circuit is further configured to generate the buffered bandgap reference voltage to compensate for a nominal voltage difference between the first bandgap reference voltage and the second bandgap reference voltage.

[0020] In various embodiments, the bandgap selector circuit is further configured to provide the bandgap translator circuit with a mode signal indicating the selected bandgap reference voltage. According to a number of embodiments, the bandgap translator circuit includes a differential amplifier operable to control a transistor by way of a feedback loop, the mode signal operable to control an impedance of a compensation circuit to maintain stability of the feedback loop. In accordance with several embodiments, the bandgap translator circuit is configured to operate as a low dropout regulator in a first state of the mode signal, and to operate as a unity gain buffer in a second state of the mode signal.

[0021] In some embodiments, the semiconductor die further includes a temperature detector configured to receive the buffered bandgap reference voltage.

[0022] In various embodiments, the semiconductor die further includes a power detector configured to receive the buffered bandgap reference voltage.

[0023] In several embodiments, the semiconductor die further includes a power amplifier and a bias circuit configured to bias the power amplifier, the bias circuit configured to receive the buffered bandgap reference voltage.

[0024] In some embodiments, the semiconductor die further includes a power management circuit configured to generate a regulated supply voltage, the power management circuit configured to receive the buffered bandgap reference voltage. According to a number of embodiments, the semiconductor die further includes a power amplifier that is powered by the regulated supply voltage.

BRIEF DESCRIPTION OF THE DRAWINGS

[0025] Embodiments of this disclosure will now be described, by way of non-limiting example, with reference to the accompanying drawings.

[0026] FIG. **1** is a schematic diagram of one example of a communication network.

[0027] FIG. **2**A is a schematic diagram of one example of a communication link using carrier aggregation.

[0028] FIG. **2**B illustrates various examples of uplink carrier aggregation for the communication link of FIG. **2**A.

[0029] FIG. **2**C illustrates various examples of downlink carrier aggregation for the communication link of FIG. **2**A.

[0030] FIG. **3**A is a schematic diagram of one example of a downlink channel using multi-input and multi-output (MIMO) communications.

[0031] FIG. **3**B is schematic diagram of one example of an uplink channel using MIMO communications.

[0032] FIG. **3**C is schematic diagram of another example of an uplink channel using MIMO communications.

[0033] FIG. **4**A is a schematic diagram of one example of a communication system that operates with beamforming.

[0034] FIG. **4**B is a schematic diagram of one example of beamforming to provide a transmit beam.

[0035] FIG. **4**C is a schematic diagram of one example of beamforming to provide a receive beam.

[0036] FIG. **5** is a schematic diagram of a multi-domain bandgap reference generator according to one embodiment.

[0037] FIG. **6**A is a schematic diagram of a low voltage bandgap reference circuit according to one embodiment.

[0038] FIG. **6**B is one example of a graph of bandgap reference voltage versus temperature for different power supply voltage levels for the low voltage bandgap reference circuit of FIG. **6**A.

[0039] FIG. **7**A is a schematic diagram of a high voltage bandgap reference circuit according to one embodiment.

[0040] FIG. **7**B is one example of a graph of bandgap reference voltage versus temperature for different power supply voltage levels for the high voltage bandgap reference circuit of FIG. **7**A.

[0041] FIG. **8**A is a schematic diagram of a coarse bandgap reference circuit according to one embodiment.

[0042] FIG. **8**B is one example of a graph of bandgap reference voltage versus temperature for different power supply voltage levels for the coarse bandgap reference circuit of FIG. **8**A.

[0043] FIG. **8**C is another example of a graph of bandgap reference voltage versus temperature for different power supply voltage levels for the coarse bandgap reference circuit of FIG. **8**A.

[0044] FIG. **9** is a schematic diagram of a bandgap selector circuit according to one embodiment.

[0045] FIG. **10**A is a schematic diagram of a bandgap translator circuit according to one embodiment.

[0046] FIG. **10**B is one example of a graph of bandgap reference voltage versus temperature for the bandgap translator circuit of FIG. **10**A.

[0047] FIG. **10**C is an expanded view of a portion of the graph of FIG. **10**B.

[0048] FIG. **11**A is one example of a graph of transient simulation results for the multi-domain bandgap reference generator of FIG. **5** at a first supply voltage level.

[0049] FIG. **11**B is one example of a graph of transient simulation results for the multi-domain bandgap reference generator of FIG. **5** at a second supply voltage level.

[0050] FIG. **12** is a schematic diagram of one embodiment of a mobile device.

[0051] FIG. **13** is a schematic diagram of a power amplifier system according to one embodiment.

[0052] FIG. **14**A is a schematic diagram of one embodiment of a packaged module.

[0053] FIG. **14**B is a schematic diagram of a cross-section of the packaged module of FIG. **14**A taken along the lines **14**B-**14**B.

DETAILED DESCRIPTION OF CERTAIN EMBODIMENTS

[0054] The following detailed description of certain embodiments presents various descriptions of specific embodiments. However, the innovations described herein can be embodied in a multitude of different ways, for example, as defined and covered by the claims. In this description, reference is made to the drawings where like reference numerals can indicate identical or functionally similar elements. It will be understood that elements illustrated in the figures are not necessarily drawn to scale. Moreover, it will be understood that certain embodiments can include more elements than illustrated in a drawing and/or a subset of the elements illustrated in a drawing. Further, some embodiments can incorporate any suitable combination of features from two or more drawings.

[0055] The International Telecommunication Union (ITU) is a specialized agency of the United Nations (UN) responsible for global issues concerning information and communication technologies, including the shared global use of radio spectrum.

[0056] The 3rd Generation Partnership Project (3GPP) is a collaboration between groups of telecommunications standard bodies across the world, such as the Association of Radio Industries and Businesses (ARIB), the Telecommunications Technology Committee (TTC), the China Communications Standards Association (CCSA), the Alliance for Telecommunications Industry Solutions (ATIS), the Telecommunications Technology Association (TTA), the European Telecommunications Standards Institute (ETSI), and the Telecommunications Standards Development Society, India (TSDSI).

[0057] Working within the scope of the ITU, 3GPP develops and maintains technical specifications for a variety of mobile communication technologies, including, for example, second generation (2G) technology (for instance, Global System for Mobile Communications (GSM) and Enhanced Data Rates for GSM Evolution (EDGE)), third generation (3G) technology (for instance, Universal Mobile Telecommunications System (UMTS) and High Speed Packet Access (HSPA)), and fourth generation (4G) technology (for instance, Long Term Evolution (LTE) and LTE-Advanced).

[0058] The technical specifications controlled by 3GPP can be expanded and revised by specification releases, which can span multiple years and specify a breadth of new features and evolutions.

[0059] In one example, 3GPP introduced carrier aggregation (CA) for LTE in Release 10. Although initially introduced with two downlink carriers, 3GPP expanded carrier aggregation in Release 14 to include up to five downlink carriers and up to three uplink carriers. Other examples of new features and evolutions provided by 3GPP releases include, but are not limited to, License Assisted Access (LAA), enhanced LAA (eLAA), Narrowband Internet of things (NB-IoT), Vehicle-to-Everything (V2X), and High Power User Equipment (HPUE).

[0060] 3GPP introduced Phase 1 of fifth generation (5G) technology in Release 15, and introduced Phase 2 of 5G technology in Release 16. Subsequent 3GPP releases will further evolve and expand 5G technology. 5G technology is also referred to herein as 5G New Radio (NR).

[0061] 5G NR supports or plans to support a variety of features, such as communications over millimeter wave spectrum, beamforming capability, high spectral efficiency waveforms, low latency communications, multiple radio numerology, and/or non-orthogonal multiple access (NOMA). Although such RF functionalities offer flexibility to networks and enhance user data rates, supporting such features can pose a number of technical challenges.

[0062] The teachings herein are applicable to a wide variety of communication systems, including, but not limited to, communication systems using advanced cellular technologies, such as LTE-Advanced, LTE-Advanced Pro, and/or 5G NR.

[0063] FIG. **1** is a schematic diagram of one example of a communication network **10**. The communication network **10** includes a macro cell base station **1**, a small cell base station **3**, and various examples of user equipment (UE), including a first mobile device **2***a*, a wireless-connected car **2***b*, a laptop **2***c*, a stationary wireless device **2***d*, a wireless-connected train **2***e*, a second mobile device **2***f*, and a third mobile device **2***g*.

[0064] Although specific examples of base stations and user equipment are illustrated in FIG. **1**, a communication network can include base stations and user equipment of a wide variety of types and/or numbers.

[0065] For instance, in the example shown, the communication network **10** includes the macro cell base station **1** and the small cell base station **3**. The small cell base station **3** can operate with relatively lower power, shorter range, and/or with fewer concurrent users relative to the macro cell base station **1**. The small cell base station **3** can also be referred to as a femtocell, a picocell, or a microcell. Although the communication network **10** is illustrated as including two base stations, the communication network **10** can be implemented to include more or fewer base stations and/or base stations of other types.

[0066] Although various examples of user equipment are shown, the teachings herein are applicable to a wide variety of user equipment, including, but not limited to, mobile phones, tablets, laptops, IoT devices, wearable electronics, customer premises equipment (CPE), wireless-connected vehicles, wireless relays, and/or a wide variety of other communication devices. Furthermore, user equipment includes not only currently available communication devices that operate in a cellular network, but also subsequently developed communication devices that will be readily implementable with the inventive systems, processes, methods, and devices as described and claimed herein.

[0067] The illustrated communication network **10** of FIG. **1** supports communications using a variety of cellular technologies, including, for example, 4G LTE and 5G NR. In certain implementations, the communication network **10** is further adapted to provide a wireless local area network (WLAN), such as WiFi. Although various examples of communication technologies have been provided, the communication network **10** can be adapted to support a wide variety of communication technologies.

[0068] Various communication links of the communication network **10** have been depicted in FIG. **1**. The communication links can be duplexed in a wide variety of ways, including, for example, using frequency-division duplexing (FDD) and/or time-division duplexing (TDD). FDD is a type of radio frequency communications that uses different frequencies for transmitting and receiving signals. FDD can provide a number of advantages, such as high data rates and low latency. In contrast, TDD is a type of radio frequency communications that uses about the same frequency for transmitting and receiving signals, and in which transmit and receive communications are switched in time. TDD can provide a number of advantages, such as efficient use of spectrum and variable allocation of throughput between transmit and receive directions.

[0069] In certain implementations, user equipment can communicate with a base station using one or more of 4G LTE, 5G NR, and WiFi technologies. In certain implementations, enhanced license assisted access (eLAA) is used to aggregate one or more licensed frequency carriers (for instance, licensed 4G LTE and/or 5G NR frequencies), with one or more unlicensed carriers (for instance, unlicensed WiFi frequencies).

[0070] As shown in FIG. **1**, the communication links include not only communication links between UE and base stations, but also UE to UE communications and base station to base station communications. For example, the communication network **10** can be implemented to support self-fronthaul and/or self-backhaul (for instance, as between mobile device **2***g* and mobile device **2***f*).

[0071] The communication links can operate over a wide variety of frequencies. In certain implementations, communications are supported using 5G NR technology over one or more frequency bands that are less than 6 Gigahertz (GHz) and/or over one or more frequency bands that are greater than 6 GHz. For example, the communication links can serve Frequency Range 1 (FR1), Frequency Range 2 (FR2), or a combination thereof. In one embodiment, one or more of the mobile devices support a HPUE power class specification.

[0072] In certain implementations, a base station and/or user equipment communicates using beamforming. For example, beamforming can be used to focus signal strength to overcome path losses, such as high loss associated with communicating over high signal frequencies. In certain embodiments, user equipment, such as one or more mobile phones, communicate using beamforming on millimeter wave frequency bands in the range of 30 GHz to 300 GHz and/or upper centimeter wave frequencies in the range of 6 GHz to 30 GHz, or more particularly, 24 GHz to 30 GHz. Cellular user equipment can communicate using beamforming and/or other techniques over a wide range of frequencies, including, for example, FR2-1 (24 GHz to 52 GHz), FR2-2 (52 GHz to 71 GHz), and/or FR1 (400 MHz to 7125 MHz).

[0073] Different users of the communication network **10** can share available network resources, such as available frequency spectrum, in a wide variety of ways.

[0074] In one example, frequency division multiple access (FDMA) is used to divide a frequency band into multiple frequency carriers. Additionally, one or more carriers are allocated to a particular user. Examples of FDMA include, but are not limited to, single carrier FDMA (SC-FDMA) and orthogonal FDMA (OFDMA). OFDMA is a multicarrier technology that subdivides the available bandwidth into multiple mutually orthogonal narrowband subcarriers, which can be separately assigned to different users.

[0075] Other examples of shared access include, but are not limited to, time division multiple access (TDMA) in which a user is allocated particular time slots for using a frequency resource, code division multiple access (CDMA) in which a frequency resource is shared amongst different users by assigning each user a unique code, space-divisional multiple access (SDMA) in which beamforming is used to provide shared access by spatial division, and non-orthogonal multiple access (NOMA) in which the power domain is used for multiple access. For example, NOMA can be used to serve multiple users at the same frequency, time, and/or code, but with different power levels.

[0076] Enhanced mobile broadband (eMBB) refers to technology for growing system capacity of LTE networks. For example, eMBB can refer to communications with a peak data rate of at least 10 Gbps and a minimum of 100 Mbps for each user. Ultra-reliable low latency communications (uRLLC) refers to technology for communication with very low latency, for instance, less than 2 milliseconds. uRLLC can be used for mission-critical communications such as for autonomous driving and/or remote surgery applications. Massive machine-type communications (mMTC) refers to low cost and low data rate communications associated with wireless connections to everyday objects, such as those associated with Internet of Things (IoT) applications.

[0077] The communication network **10** of FIG. **1** can be used to support a wide variety of advanced communication features, including, but not limited to, eMBB, uRLLC, and/or mMTC.

[0078] FIG. **2**A is a schematic diagram of one example of a communication link using carrier aggregation. Carrier aggregation can be used to widen bandwidth of the communication link by supporting communications over multiple frequency carriers, thereby increasing user data rates and enhancing network capacity by utilizing fragmented spectrum allocations.

[0079] In the illustrated example, the communication link is provided between a base station **21** and a mobile device **22**. As shown in FIG. **2**A, the communications link includes a downlink channel used for RF communications from the base station **21** to the mobile device **22**, and an uplink channel used for RF communications from the mobile device **22** to the base station **21**.

[0080] Although FIG. **2**A illustrates carrier aggregation in the context of FDD communications, carrier aggregation can also be used for TDD communications.

[0081] In certain implementations, a communication link can provide asymmetrical data rates for a downlink channel and an uplink channel. For example, a communication link can be used to support a relatively high downlink data rate to enable high speed streaming of multimedia content to a mobile device, while providing a relatively slower data rate for uploading data from the mobile device to the cloud.

[0082] In the illustrated example, the base station **21** and the mobile device **22** communicate via carrier aggregation, which can be used to selectively increase bandwidth of the communication link. Carrier aggregation includes contiguous aggregation, in which contiguous carriers within the same operating frequency band are aggregated. Carrier aggregation can also be non-contiguous, and can include carriers separated in frequency within a common band or in different bands.

[0083] In the example shown in FIG. **2**A, the uplink channel includes three aggregated component carriers f_{UL1}, f_{UL2}, and f_{UL3}. Additionally, the downlink channel includes five aggregated component carriers f_{DL1}, f_{DL2}, f_{DL3}, f_{DL4}, and f_{DL5}. Although one example of component carrier aggregation is shown, more or fewer carriers can be aggregated for uplink and/or downlink. Moreover, a number of aggregated carriers can be varied over time to achieve desired uplink and downlink data rates.

[0084] For example, a number of aggregated carriers for uplink and/or downlink communications with respect to a particular mobile device can change over time. For example, the number of aggregated carriers can change as the device moves through the communication network and/or as network usage changes over time.

[0085] FIG. **2**B illustrates various examples of uplink carrier aggregation for the communication link of FIG. **2**A. FIG. **2**B includes a first carrier aggregation scenario **31**, a second carrier aggregation scenario **32**, and a third carrier aggregation scenario **33**, which schematically depict three types of carrier aggregation.

[0086] The carrier aggregation scenarios **31-33** illustrate different spectrum allocations for a first component carrier f_{UL1}, a second component carrier f_{UL2}, and a third component carrier f_{UL3}. Although FIG. **2**B is illustrated in the context of aggregating three component carriers, carrier aggregation can be used to aggregate more or fewer carriers. Moreover, although illustrated in the context of uplink, the aggregation scenarios are also applicable to downlink.

[0087] The first carrier aggregation scenario **31** illustrates intra-band contiguous carrier aggregation, in which component carriers that are adjacent in frequency and in a common frequency band are aggregated. For example, the first carrier aggregation scenario **31** depicts aggregation of component carriers f_{UL1}, f_{UL2}, and f_{UL3} that are contiguous and located within a first frequency band BAND**1**.

[0088] With continuing reference to FIG. **2**B, the second carrier aggregation scenario **32** illustrates intra-band non-continuous carrier aggregation, in which two or more components carriers that are non-adjacent in frequency and within a common frequency band are aggregated. For example, the second carrier aggregation scenario **32** depicts aggregation of component carriers f_{UL1}, f_{UL2}, and f_{UL3} that are non-contiguous, but located within a first frequency band BAND**1**.

[0089] The third carrier aggregation scenario **33** illustrates inter-band non-contiguous carrier aggregation, in which component carriers that are non-adjacent in frequency and in multiple frequency bands are aggregated. For example, the third carrier aggregation scenario **33** depicts aggregation of component carriers f_{UL1} and f_{UL2} of a first frequency band BAND**1** with component carrier f_{UL3} of a second frequency band BAND**2**.

[0090] FIG. **2**C illustrates various examples of downlink carrier aggregation for the communication link of FIG. **2**A. The examples depict various carrier aggregation scenarios **34-38** for different spectrum allocations of a first component carrier f_{DL1}, a second component carrier f_{DL2}, a third component carrier f_{DL3}, a fourth component carrier f_{DL4}, and a fifth component carrier f_{DL5}. Although FIG. **2**C is illustrated in the context of aggregating five component carriers, carrier aggregation can be used to aggregate more or fewer carriers. Moreover, although illustrated in the context of downlink, the aggregation scenarios are also applicable to uplink.

[0091] The first carrier aggregation scenario **34** depicts aggregation of component carriers that are contiguous and located within the same frequency band. Additionally, the second carrier aggregation scenario **35** and the third carrier aggregation scenario **36** illustrates two examples of aggregation that are non-contiguous, but located within the same frequency band. Furthermore, the fourth carrier aggregation scenario **37** and the fifth carrier aggregation scenario **38** illustrates two examples of aggregation in which component carriers that are non-adjacent in frequency and in multiple frequency bands are aggregated. As a number of aggregated component carriers increases, a complexity of possible carrier aggregation scenarios also increases.

[0092] With reference to FIGS. **2**A-**2**C, the individual component carriers used in carrier aggregation can be of a variety of frequencies, including, for example, frequency carriers in the same band or in multiple bands. Additionally, carrier aggregation is applicable to implementations in which the individual component carriers are of about the same bandwidth as well as to implementations in which the individual component carriers have different bandwidths.

[0093] Certain communication networks allocate a particular user device with a primary component carrier (PCC) or anchor carrier for uplink and a PCC for downlink. Additionally, when the mobile device communicates using a single frequency carrier for uplink or downlink, the user device communicates using the PCC. To enhance bandwidth for uplink communications, the uplink PCC can be aggregated with one or more uplink secondary component carriers (SCCs). Additionally, to enhance bandwidth for downlink communications, the downlink PCC can be aggregated with one or more downlink SCCs.

[0094] In certain implementations, a communication network provides a network cell for each component carrier. Additionally, a primary cell can operate using a PCC, while a secondary cell can operate using a SCC. The primary and secondary cells may have different coverage areas, for instance, due to differences in frequencies of carriers and/or network environment.

[0095] License assisted access (LAA) refers to downlink carrier aggregation in which a licensed frequency carrier associated with a mobile operator is aggregated with a frequency carrier in unlicensed spectrum, such as WiFi. LAA employs a downlink PCC in the licensed spectrum that carries control and signaling information associated with the communication link, while unlicensed spectrum is aggregated for wider downlink bandwidth when available. LAA can operate with dynamic adjustment of secondary carriers to avoid WiFi users and/or to coexist with WiFi users. Enhanced license assisted access (eLAA) refers to an evolution of LAA that aggregates licensed and unlicensed spectrum for both downlink and uplink. Furthermore, NR-U can operate on top of LAA/eLAA over a 5 GHz band (5150 to 5925 MHz) and/or a 6 GHz band (5925 MHz to 7125 MHz).

[0096] FIG. **3**A is a schematic diagram of one example of a downlink channel using multi-input and multi-output (MIMO) communications. FIG. **3**B is schematic diagram of one example of an uplink channel using MIMO communications.

[0097] MIMO communications use multiple antennas for simultaneously communicating multiple data streams over common frequency spectrum. In certain implementations, the data streams operate with different reference signals to enhance data reception at the receiver. MIMO communications benefit from higher SNR, improved coding, and/or reduced signal interference due to spatial multiplexing differences of the radio environment.

[0098] MIMO order refers to a number of separate data streams sent or received. For instance, MIMO order for downlink communications can be described by a number of transmit antennas of a base station and a number of receive antennas for UE, such as a mobile device. For example, two-by-two (2×2) DL MIMO refers to MIMO downlink communications using two base station antennas and two UE antennas. Additionally, four-by-four (4×4) DL MIMO refers to MIMO downlink communications using four base station antennas and four UE antennas.

[0099] In the example shown in FIG. **3**A, downlink MIMO communications are provided by transmitting using M antennas **43***a*, **43***b*, **43***c*, . . . **43***m* of the base station **41** and receiving using N antennas **44***a*, **44***b*, **44***c*, . . . **44***n* of the mobile device **42**. Accordingly, FIG. **3**A illustrates an example of m×n DL MIMO.

[0100] Likewise, MIMO order for uplink communications can be described by a number of transmit antennas of UE, such as a mobile device, and a number of receive antennas of a base station. For example, 2×2 UL MIMO refers to MIMO uplink communications using two UE antennas and two base station antennas. Additionally, 4×4 UL MIMO refers to MIMO uplink communications using four UE antennas and four base station antennas.

[0101] In the example shown in FIG. **3**B, uplink MIMO communications are provided by transmitting using N antennas **44***a*, **44***b*, **44***c*, . . . **44***n* of the mobile device **42** and receiving using M antennas **43***a*, **43***b*, **43***c*, . . . **43***m* of the base station **41**. Accordingly, FIG. **3**B illustrates an example of n×m UL MIMO.

[0102] By increasing the level or order of MIMO, bandwidth of an uplink channel and/or a downlink channel can be increased.

[0103] MIMO communications are applicable to communication links of a variety of types, such as FDD communication links and TDD communication links.

[0104] FIG. **3**C is schematic diagram of another example of an uplink channel using MIMO communications. In the example shown in FIG. **3**C, uplink MIMO communications are provided by transmitting using N antennas **44***a*, **44***b*, **44***c*, . . . **44***n* of the mobile device **42**. Additional a first portion of the uplink transmissions are received using M antennas **43***a***1**, **43***b***1**, **43***c***1**, . . . **43***m***1** of a first base station **41***a*, while a second portion of the uplink transmissions are received using M antennas **43***a***2**, **43***b***2**, **43***c***2**, . . . **43***m***2** of a second base station **41***b*. Additionally, the first base station **41***a* and the second base station **41***b* communication with one another over wired, optical, and/or wireless links.

[0105] The MIMO scenario of FIG. **3**C illustrates an example in which multiple base stations cooperate to facilitate MIMO communications.

[0106] FIG. **4**A is a schematic diagram of one example of a communication system **110** that operates with beamforming. The communication system **110** includes a transceiver **105**, signal conditioning circuits **104***a***1**, **104***a***2** . . . **104***an*, **104***b***1**, **104***b***2** . . . **104***bn*, **104***m***1**, **104***m***2** . . . **104***mn*, and an antenna array **102** that includes antenna elements **103***a***1**, **103***a***2** . . . **103***an*, **103***b***1**, **103***b***2** . . . **103***bn*, **103***m***1**, **103***m***2** . . . **103***mn*.

[0107] Communications systems that communicate using millimeter wave carriers (for instance, 30 GHz to 300 GHz), centimeter wave carriers (for instance, 3 GHz to 30 GHz), and/or other frequency carriers can employ an antenna array to provide beam formation and directivity for transmission and/or reception of signals.

[0108] For example, in the illustrated embodiment, the communication system **110** includes an array **102** of m×n antenna elements, which are each controlled by a separate signal conditioning circuit, in this embodiment. As indicated by the ellipses, the communication system **110** can be implemented with any suitable number of antenna elements and signal conditioning circuits.

[0109] With respect to signal transmission, the signal conditioning circuits can provide transmit signals to the antenna array **102** such that signals radiated from the antenna elements combine using constructive and destructive interference to generate an aggregate transmit signal exhibiting beam-like qualities with more signal strength propagating in a given direction away from the antenna array **102**.

[0110] In the context of signal reception, the signal conditioning circuits process the received signals (for instance, by separately controlling received signal phases) such that more signal energy is received when the signal is arriving at the antenna array **102** from a particular direction. Accordingly, the communication system **110** also provides directivity for reception of signals.

[0111] The relative concentration of signal energy into a transmit beam or a receive beam can be enhanced by increasing the size of the array. For example, with more signal energy focused into a transmit beam, the signal is able to propagate for a longer range while providing sufficient signal level for RF communications. For instance, a signal with a large proportion of signal energy focused into the transmit beam can exhibit high effective isotropic radiated power (EIRP).

[0112] In the illustrated embodiment, the transceiver **105** provides transmit signals to the signal conditioning circuits and processes signals received from the signal conditioning circuits. As shown in FIG. **4**A, the transceiver **105** generates control signals for the signal conditioning circuits. The control signals can be used for a variety of functions, such as controlling the gain and phase of transmitted and/or received signals to control beamforming.

[0113] FIG. **4**B is a schematic diagram of one example of beamforming to provide a transmit beam. FIG. **4**B illustrates a portion of a communication system including a first signal conditioning circuit **114***a*, a second signal conditioning circuit **114***b*, a first antenna element **113***a*, and a second antenna element **113***b*.

[0114] Although illustrated as included two antenna elements and two signal conditioning circuits, a communication system can include additional antenna elements and/or signal conditioning circuits. For example, FIG. **4**B illustrates one embodiment of a portion of the communication system **110** of FIG. **4**A.

[0115] The first signal conditioning circuit **114***a* includes a first phase shifter **130***a*, a first power amplifier **131***a*, a first low noise amplifier (LNA) **132***a*, and switches for controlling selection of the power amplifier **131***a* or LNA **132***a*. Additionally, the second signal conditioning circuit **114***b* includes a second phase shifter **130***b*, a second power amplifier **131***b*, a second LNA **132***b*, and switches for controlling selection of the power amplifier **131***b* or LNA **132***b*.

[0116] Although one embodiment of signal conditioning circuits is shown, other implementations of signal conditioning circuits are possible. For instance, in one example, a signal conditioning circuit includes one or more band filters, duplexers, and/or other components.

[0117] In the illustrated embodiment, the first antenna element **113***a* and the second antenna element **113***b* are separated by a distance d. Additionally, FIG. **4**B has been annotated with an angle θ, which in this example has a value of about 90° when the transmit beam direction is substantially perpendicular to a plane of the antenna array and a value of about 0° when the transmit beam direction is substantially parallel to the plane of the antenna array.

[0118] By controlling the relative phase of the transmit signals provided to the antenna elements **113***a*, **113***b*, a desired transmit beam angle θ can be achieved. For example, when the first phase shifter **130***a* has a reference value of 0°, the second phase shifter **130***b* can be controlled to provide a phase shift of about $-2\pi f(d/v)\cos\theta$ radians, where f is the fundamental frequency of the transmit signal, d is the distance between the antenna elements, v is the velocity of the radiated wave, and π is the mathematic constant pi.

[0119] In certain implementations, the distance d is implemented to be about $\frac{1}{2}\lambda$, where λ is the wavelength of the fundamental component of the transmit signal. In such implementations, the second phase shifter **130***b* can be controlled to provide a phase shift of about $-\pi\cos\theta$ radians to achieve a transmit beam angle θ.

[0120] Accordingly, the relative phase of the phase shifters **130***a*, **130***b* can be controlled to provide transmit beamforming. In certain implementations, a baseband processor and/or a transceiver (for example, the transceiver **105** of FIG. **4**A) controls phase values of one or more phase shifters and gain values of one or more controllable amplifiers to control beamforming.

[0121] FIG. **4**C is a schematic diagram of one example of beamforming to provide a receive beam. FIG. **4**C is similar to FIG. **4**B, except that FIG. **4**C illustrates beamforming in the context of a receive beam rather than a transmit beam.

[0122] As shown in FIG. **4**C, a relative phase difference between the first phase shifter **130***a* and the second phase shifter **130***b* can be selected to about equal to $-\pi f(d/v)\cos\theta$ radians to achieve a desired receive beam angle θ. In implementations in which the distance d corresponds to about $\frac{1}{2}\lambda$, the phase difference can be selected to about equal to $-\pi\cos\theta$ radians to achieve a receive beam angle θ.

[0123] Although various equations for phase values to provide beamforming have been provided, other phase selection values are possible, such as phase values selected based on implementation of an antenna array, implementation of signal conditioning circuits, and/or a radio environment.

Bandgap Reference Generation for Multiple Power Supply Domains

[0124] Provided herein are bandgap reference generators suitable for operating in multiple power supply domains. In certain embodiments, a bandgap reference generator includes a low voltage bandgap reference circuit that generates a first bandgap reference voltage, a high voltage bandgap reference circuit that generates a second bandgap reference voltage, a bandgap selector circuit that outputs the first bandgap reference voltage or the second bandgap reference voltage as a selected bandgap reference voltage based on a voltage level of the power supply voltage, and a bandgap translator circuit that generates a buffered bandgap reference voltage based on the selected bandgap reference voltage.

[0125] By implementing the bandgap reference generator in this manner, enhanced flexibility is provided by allowing the bandgap reference generator to operate with different voltage levels of the power supply voltage. Thus, the buffered bandgap reference voltage serves as an accurate reference voltage in a wide range of deployment scenarios associated with different power supply domains. Accordingly, the bandgap reference generator avoids a need for custom designs targeted for a particular power supply domain and/or reduces or eliminates constraints on power supply voltage.

[0126] Thus, the bandgap reference generator overcomes limitations of the low voltage bandgap reference circuit and the high voltage bandgap reference circuit by selecting an appropriate bandgap reference voltage based on the voltage level of the power supply voltage. For example, the low voltage bandgap reference circuit can operate over a first range of the power supply voltage, while the high voltage bandgap reference circuit can operate over a second range of the power supply voltage greater than the first range.

[0127] In certain implementations, the bandgap reference generator further includes a coarse bandgap reference circuit that generates a third bandgap reference voltage, which the bandgap selector circuit compares to the voltage level of the power supply voltage to aid in selecting the appropriate bandgap reference voltage.

[0128] Although the coarse bandgap reference voltage is of a lower precision than the first bandgap reference voltage and the second bandgap reference voltage, the coarse bandgap reference circuit operates over a wider range of the power supply voltage than the individual ranges of the low voltage bandgap reference circuit and the high voltage bandgap reference circuit. Thus, the coarse bandgap reference voltage is well-suited for comparing to the voltage level of the power supply voltage to aid in bandgap reference voltage selection.

[0129] In certain implementations, the bandgap translator circuit outputs multiple reference voltages by scaling the buffered bandgap reference voltage by different scaling factors. This in turn enhances flexibility by providing downstream circuitry with a wide range of reference voltage levels available for use.

[0130] In certain implementations, the bandgap translator circuit operates to compensate for a nominal voltage difference between the first bandgap reference voltage and the second bandgap reference voltage. Implementing the bandgap translator circuit in this manner aids in providing a substantially constant voltage level of the buffered bandgap reference voltage across operating conditions.

[0131] In certain implementations, the bandgap selector circuit provides the bandgap translator circuit with a mode signal indicating the selected bandgap reference voltage. The mode signal can serve a wide variety of functions, including, but not limited to, aiding the bandgap translator circuit in compensating for a nominal voltage difference between the first bandgap reference voltage and the second bandgap reference voltage.

[0132] For instance, the bandgap translator circuit can operate as a low dropout regulator when the mode signal indicates the first bandgap reference voltage is selected, and as a unity gain buffer when the mode signal indicates the second bandgap reference voltage is selected. Additionally, a gain from output to input of the low dropout regulator can correspond to the ratio of the second bandgap reference voltage to the first bandgap reference voltage, thereby compensating for the nominal voltage difference.

[0133] In certain implementations, the mode signal controls an impedance of a compensation circuit of the bandgap translator circuit, thereby maintaining stability of a feedback loop of the bandgap translator circuit.

[0134] In certain implementations, the bandgap reference generator is included on a semiconductor die of a front end system. Thus, the bandgap reference generator can serve to generate high precision reference voltages for a range of applications, including, but not limited to, on-die power sensing, on-die temperature sensing, fine-tuning biasing voltage/current generation, generating a high voltage supply voltage (for instance, 2.5V±10% or 3.3V±10%) of a power amplifier, generating a low voltage supply voltage (for instance, 1.2V±10%) for a low power/high speed compact digital core (which can include, for instance, a serial interface such as Mobile Industry Processor Interface (MIPI) and decoders realized in a low voltage/small feature size complementary metal-oxide-semiconductor (CMOS) technology), and/or generating a supply voltage (for instance, 1.8V±10%) for high performance analog blocks.

[0135] Thus, the bandgap reference generator provides references voltages in applications with multiple power supply voltage domains, for instance, high performance front end modules for millimeter wave (mmW) communications.

[0136] In certain implementations, the bandgap reference generator generates a low power supply voltage (1.2V±10%)/high-precision bandgap reference voltage (Vbg~700 mV), a higher power supply voltage (1.8V±10% and 2.5V to 3.3V applications)/high-precision bandgap reference voltage (Vbg~1110 mV), and a coarse bandgap reference voltage (Vbg~920 mV) across both 1.2V±10% standard and 1.8V±10% domain or higher supply voltage domains.

[0137] Additionally, the bandgap reference generator further includes a bandgap reference voltage selector operating over wide power supply range (from 1.08V to 1.98V) to determine whether to select the sub-1V bandgap reference voltage for low power supply voltage domains (1.2V±10%) or the >1V bandgap reference voltage for higher power supply voltage domains. Furthermore, the bandgap reference voltage selector makes the selection based by using the coarse bandgap reference voltage in a comparison operation. The bandgap reference generator further includes a multiple-output dual-input-mode bandgap reference voltage translator operating in wide power supply range (from 1.08V to 1.98V) to generate various high precision reference voltages for various applications.

[0138] FIG. **5** is a schematic diagram of a multi-domain bandgap reference generator **150** according to one embodiment. The multi-domain bandgap reference generator **150** includes a low voltage bandgap reference circuit **141**, a high voltage bandgap reference circuit **142**, a coarse bandgap reference circuit **143**, a bandgap selector circuit **144**, and a bandgap translator circuit **145**. The multi-domain bandgap reference generator **150** is also referred to herein as the bandgap reference generator **150**.

[0139] The bandgap reference generator **150** receives a power supply voltage V_{DD} and a ground voltage V_{SS}. The bandgap reference generator **150** operates over a wide range of voltage levels of the power supply voltage V_{DD}, thereby providing suitable reference voltages for a wide range of applications and operating scenarios.

[0140] As shown in FIG. **5**, the low voltage bandgap reference circuit **141** generates a first or low voltage bandgap reference voltage V_{BG_LV}, the high voltage bandgap reference circuit **142** generates a second or high voltage bandgap reference voltage V_{BG_HV}, and the coarse bandgap reference circuit **143** generates a third or coarse bandgap reference voltage V_{BG_COARSE}.

[0141] The low voltage bandgap reference circuit **141** and the high voltage bandgap reference circuit **142** are suitable for operating over different ranges of the power supply voltage V_{DD}, such as a low voltage range and a high voltage range, respectively. Additionally, the coarse bandgap reference circuit **143** can operate over a wide voltage range (for instance, covering both the low voltage range and the high voltage range).

[0142] In the illustrated embodiment, the bandgap selector circuit **144** receives the low voltage bandgap reference voltage V_{BG_LV}, the high voltage bandgap reference voltage V_{BG_HV}, and the coarse bandgap reference voltage V_{BG_COARSE}. Additionally, the bandgap selector circuit **144** generates a selected bandgap voltage $V_{BG\_SELECTED}$ based on selecting the low voltage bandgap reference voltage V_{BG_LV} or the high voltage bandgap reference voltage V_{BG_HV}. The bandgap selector circuit **144** also generates a mode signal MODE indicating which bandgap reference voltage is selected, in this embodiment.

[0143] In certain implementations, the bandgap selector circuit **144** chooses the selected bandgap voltage $V_{BG\_SELECTED}$ based on comparing the power supply voltage V_{DD} to the coarse bandgap reference voltage V_{BG_COARSE}. For example, the bandgap selector circuit **144** can select the low voltage bandgap reference voltage V_{BG_LV} when α^*V_{DD} is less than the coarse bandgap reference voltage V_{BG_COARSE}, and select the high voltage bandgap reference voltage V_{BG_HV} when α^*V_{DD} is greater than or equal to the coarse bandgap reference voltage V_{BG_COARSE}, where α is scaling factor. In one example, α is controlled by a ratio of resistors of a voltage divider.

[0144] The bandgap translator circuit **145** receives the selected bandgap voltage $V_{BG\_SELECTED}$ and the mode signal MODE, and generates a buffered bandgap voltage $V_{BG\_BUFFERED}$ and multiple reference voltages V_{REFA}, V_{REFB}, . . . V_{REFN} that are scaled in relation to the buffered bandgap voltage $V_{BG\_BUFFERED}$ by various scaling factors. The bandgap translator circuit **145** can serve to provide sufficient drive strength of the buffered bandgap voltage $V_{BG\_BUFFERED}$ for a wide range of applications and types of downstream circuitry.

[0145] In certain implementations, the bandgap translator circuit **145** serves to generate the buffered bandgap voltage $V_{BG\_BUFFERED}$ to compensate for a nominal voltage difference between the low voltage bandgap reference voltage V_{BG_LV} and the high voltage bandgap reference voltage V_{BG_HV}.

[0146] The mode signal MODE can aid the bandgap translator circuit **145** in processing the selected bandgap voltage $V_{BG\_SELECTED}$ by indicating a voltage level of the selected bandgap voltage $V_{BG\_SELECTED}$. In certain implementations, the bandgap translator circuit **145** changes a gain or scaling between the buffered bandgap voltage $V_{BG\_BUFFERED}$ and the selected bandgap voltage $V_{BG\_SELECTED}$ based on the mode signal MODE.

[0147] In one example, the bandgap translator circuit **145** operates as a low dropout regulator when the mode signal MODE indicates the low voltage bandgap reference voltage V_{BG_LV} is selected, and as a unity gain buffer when the mode signal MODE indicates the high voltage bandgap reference voltage V_{BG_HV} is selected. Additionally, a gain from output to input of the low dropout regulator can correspond to the ratio of the high voltage bandgap reference voltage V_{BG_HV} to the low voltage bandgap reference voltage V_{BG_LV}, thereby compensating for the nominal voltage difference.

[0148] FIG. **6**A is a schematic diagram of a low voltage bandgap reference circuit **210** according to one embodiment. The low voltage bandgap reference circuit **210** includes a first p-type field effect transistor (PFET) **191**, a second PFET **192**, a third PFET **193**, a fourth PFET **194**, a differential amplifier **195** (for instance, an operational amplifier), a resistor array **196**, a diode array **197**, a first resistor **198**, and a second resistor **199**. The low voltage bandgap reference circuit **210** receives a power supply voltage V_{DD} and a ground voltage V_{SS}, and generates a low voltage bandgap reference voltage V_{BG_LV}.

[0149] The low voltage bandgap reference circuit **210** of FIG. **6**A illustrates one embodiment of the low voltage bandgap reference circuit **141** of FIG. **5**. However, the teachings herein are applicable to low voltage bandgap reference circuits implemented in other ways.

[0150] In the illustrated embodiment, the resistor array **196** includes an array of nine resistor elements including one resistor element **201** serving as a resistor R**1** and eight resistor elements **202***a*-**202***h*, respectively, serving as a resistor R**2**, with R**1**:R**2**=1:N. Implementing R**1** and R**2** using the resistor array **196** aids in providing enhanced matching in the presence of process variation.

[0151] As shown in FIG. **6**A, the diode array **197** includes an array of nine diode elements including one diode element **203** serving as a diode D**1** and eight diode elements **204***a*-**204***h*, respectively, serving as a diode D**2**, with D**1**:D**2**=1:8. Implementing D**1** and D**2** using the diode array **197** aids in providing enhanced matching.

[0152] The differential amplifier **195** operates with feedback to control the gate voltages of PFETs **191**-**194**, thereby controlling the currents flowing therethrough. In the illustrated embodiment, I_1:I_2:I_3=1:1:2. In certain implementations, the PFETs correspond to p-type metal oxide semiconductor (PMOS) transistors.

[0153] FIG. **6**B is one example of a graph of bandgap reference voltage versus temperature for different power supply voltage levels for the low voltage bandgap reference circuit **210** of FIG. **6**A. In the example of FIG. **6**B, the low voltage bandgap reference circuit **210** outputs a reference voltage of about 700 mV for V_{DD} between about 1.08 V and about 1.32V.

[0154] FIG. **7**A is a schematic diagram of a high voltage bandgap reference circuit **230** according to one embodiment. The high voltage bandgap reference circuit **230** includes a first PFET **211**, a second PFET **212**, a third PFET **213**, a differential amplifier **215**, a resistor array **216**, and a diode array **217**. The high voltage bandgap reference circuit **230** receives a power supply voltage V_{DD} and a ground voltage V_{SS}, and generates a high voltage bandgap reference voltage V_{BG_HV}.

[0155] The high voltage bandgap reference circuit **230** of FIG. **7**A illustrates one embodiment of the high voltage bandgap reference circuit **142** of FIG. **5**. However, the teachings herein are applicable to high voltage bandgap reference circuits implemented in other ways.

[0156] In the illustrated embodiment, the resistor array **216** includes an array of nine resistor elements including one resistor element **221** serving as a resistor R**1** and eight resistor elements **222***a*-**222***h*, respectively, serving as a resistor R**2**, with R**1**:R**2**=1:N.

[0157] As shown in FIG. **7**A, the diode array **217** includes an array of fifteen diode elements including one diode element **233** serving as a diode D**1**, thirteen diode elements **234***a*-**234***m*, respectively, serving as a diode D**2**, and one diode element **235** serving as a diode D**3**, with D**1**:D**2**:D**3**=1:13:1.

[0158] The differential amplifier **215** operates with feedback to control the gate voltages of PFETs **211**-**213**, thereby controlling the currents flowing therethrough. In the illustrated embodiment, I_1:I_2:I_3=1:1:1.

[0159] FIG. **7**B is one example of a graph of bandgap reference voltage versus temperature for different power supply voltage levels for the high voltage bandgap reference circuit **230** of FIG. **7**A. In the example of FIG. **7**B, the high voltage bandgap reference circuit **230** outputs a reference voltage of about 1110 mV with very low temperature coefficient for V_{DD} between about 1.6V and about 1.98V. Additionally, the temperature coefficient is relatively low for V_{DD} between about 1.32V and about 1.6V.

[0160] FIG. **8**A is a schematic diagram of a coarse bandgap reference circuit **280** according to one embodiment. The coarse bandgap reference circuit **280** includes a PMOS-diode based bandgap core **240**, a first output control n-type field effect transistor (NFET) **241**, a second output control NFET **242**, a first temperature compensation NFET **243**, a second temperature compensation NFET **244**, a first voltage dividing resistor **245**, a second voltage dividing resistor **246**, and a comparator **248**. The coarse bandgap reference circuit **280** receives a power supply voltage V_{DD} and a ground voltage V_{SS}, and generates a coarse bandgap reference voltage V_{BG_COARSE}.

[0161] The coarse bandgap reference circuit **280** of FIG. **8**A illustrates one embodiment of the coarse bandgap reference circuit **143** of FIG. **5**. However, the teachings herein are applicable to coarse bandgap reference circuits implemented in other ways.

[0162] As shown in FIG. **8**A, the PMOS-diode based bandgap core **240** includes a first PFET **251**, a second PFET

252, a third PFET **253**, a fourth PFET **254**, a fifth PFET **255**, a sixth PFET **256**, a first output resistor **261**, a second output resistor **262**, a third output resistor **263**, and a differential amplifier **265**.

[0163] In the illustrated embodiment, the comparator **248** includes a hysteretic differential amplifier **271**, a first inverting buffer **275**, and a second inverting buffer **276**. When the voltage level of the supply voltage V_{DD} is relatively high compared to the coarse bandgap reference voltage V_{BG_COARSE}, the comparator **248** activates the first temperature compensation NFET **243** for temperature control and deactivates the first output control NFET **241**. However, when the voltage level of the supply voltage V_{DD} is relatively low compared to the coarse bandgap reference voltage V_{BG_COARSE}, the comparator **248** activates the first output control NFET **241** for output voltage control and deactivates the first temperature compensation NFET **243**. The threshold for comparison in based on a ratio of the first voltage dividing resistor **245** and the second voltage dividing resistor **246**, which in one example is 6:9.

[0164] FIG. **8**B is one example of a graph of bandgap reference voltage versus temperature for different power supply voltage levels for the coarse bandgap reference circuit **280** of FIG. **8**A. FIG. **8**C is another example of a graph of bandgap reference voltage versus temperature for different power supply voltage levels for the coarse bandgap reference circuit **280** of FIG. **8**A.

[0165] In the examples of FIGS. **8**B and **8**C, the coarse bandgap reference circuit **280** outputs a reference voltage of about 920 mV+/−2.4%.

[0166] As shown by a comparison of FIGS. **8**B and **8**C to FIGS. **6**B and **7**B, the coarse bandgap reference circuit **280** operates over a wider voltage range than the low voltage bandgap reference circuit **210** and the high voltage bandgap reference circuit **230** individually, but with a poorer temperature coefficient.

[0167] FIG. **9** is a schematic diagram of a bandgap selector circuit **320** according to one embodiment. The bandgap selector circuit **320** includes a first voltage divider resistor **301**, a second voltage divider resistor **302**, a hysteretic comparator **303**, a first inverting buffer **305**, a second inverting buffer **306**, a first pass gate PFET **311**, a second pass gate PFET **312**, a first pass gate NFET **313**, and a second pass gate NFET **314**. The bandgap selector circuit **320** receives a power supply voltage V_{DD}, a ground voltage V_{SS}, a coarse bandgap reference voltage V_{BG_COARSE}, a low voltage bandgap reference voltage V_{BG_LV}, and a high voltage bandgap reference voltage V_{BG_HV}. Additionally, the bandgap selector circuit **320** generates a selected bandgap reference voltage $V_{BG\_SELECTED}$ and a mode signal MODE.

[0168] The bandgap selector circuit **320** of FIG. **9** illustrates one embodiment of the bandgap selector circuit **144** of FIG. **5**. However, the teachings herein are applicable to bandgap selector circuits implemented in other ways.

[0169] In the illustrated embodiment, the first voltage divider resistor **301** and the second voltage divider resistor **302** operate as a voltage divider between the power supply voltage V_{DD} and the ground voltage V_{SS}. The ratio α of the voltage divider (corresponding to the ratio of the divided voltage output from the divider to the power supply voltage V_{DD}) can be any suitable value, for instance, 0.6.

[0170] Additionally, the hysteretic comparator **303** compares the divided voltage from the voltage divider to the coarse bandgap reference voltage V_{BG_COARSE} to select either the low voltage bandgap reference voltage V_{BG_LV} or the high voltage bandgap reference voltage V_{BG_HV} as the selected bandgap reference voltage $V_{BG\_SELECTED}$. Accordingly, the bandgap selector circuit **320** generates the selected bandgap reference voltage $V_{BG\_SELECTED}$ based on comparing the power supply voltage V_{DD} to the coarse bandgap reference voltage V_{BG_COARSE}.

[0171] As shown in FIG. **9**, the mode signal MODE is used to control the pass gate transistors **311-314**, and thus indicates which bandgap reference voltage is selected.

[0172] FIG. **10**A is a schematic diagram of a bandgap translator circuit **380** according to one embodiment. The bandgap translator circuit **380** includes a differential amplifier **350**, a first feedback resistor **351**, a second feedback resistor **352**, a PFET **353**, a first compensation resistor **355**, a second compensation resistor **356**, a compensation capacitor **357**, a bypass NFET **358**, a bypass PFET **359**, and voltage dividing resistors **361***a*, **361***b*, **361***c*, . . . **361***m*. The bandgap translator circuit **380** receives a power supply voltage V_{DD}, a ground voltage V_{SS}, a mode signal MODE, and a selected bandgap reference voltage $V_{BG\_SELECTED}$. Additionally, the bandgap translator circuit **380** generates a buffered bandgap reference voltage $V_{BG\_BUFFERED}$ and multiple reference voltages V_{REFA}, V_{REFB}, . . . V_{REFN} that are scaled in relation to the buffered bandgap voltage $V_{BG\_BUFFERED}$ by various scaling factors.

[0173] The bandgap translator circuit **380** of FIG. **10**A illustrates one embodiment of the bandgap translator circuit **145** of FIG. **5**. However, the teachings herein are applicable to bandgap translator circuits implemented in other ways.

[0174] In the illustrated embodiment, the bandgap translator circuit **380** operates as a low dropout regulator when the mode signal MODE indicates the low voltage bandgap reference voltage V_{BG_LV} is selected, and as a unity gain buffer when the mode signal MODE indicates the high voltage bandgap reference voltage V_{BG_HV} is selected. Thus, when the low voltage bandgap reference voltage V_{BG_LV} is selected, the buffered bandgap voltage $V_{BG\_BUFFERED}$ is about equal to V_{BG_LV}*(Rfb1+Rfb2)/Rfb1, where Rfb1 and Rfb2 are the resistances of the first feedback resistor **351** and the second feedback resistor **352**, respectively.

[0175] Implementing the bandgap translator circuit **380** in this manner aids in compensation for a nominal voltage difference between the low voltage bandgap reference voltage V_{BG_LV} and the high voltage bandgap reference voltage V_{BG_HV}.

[0176] In the illustrated embodiment, the mode signal MODE is also used to control an impedance using for frequency compensation, thereby maintaining stability. For example, the second compensation resistor **356** is selectively bypassed based on the mode signal MODE, in this example.

[0177] FIG. **10**B is one example of a graph of bandgap reference voltage versus temperature for the bandgap translator circuit **380** of FIG. **10**A. In the example of FIG. **10**B, the bandgap translator circuit outputs about 1110 mV for V_{DD} from 1.08V to about 1.98V, thereby covering both low voltage and high voltage domains. The bandgap reference voltage exhibits excellent temperature stability over a temperature range of about −40° C. to about 125° C.

[0178] FIG. **10**C is an expanded view of a portion of the graph of FIG. **10**B.

[0179] FIG. **11**A is one example of a graph of transient simulation results for the multi-domain bandgap reference generator **150** of FIG. **5** at a supply voltage level of 1.8V.

[0180] FIG. **11**B is one example of a graph of transient simulation results for the multi-domain bandgap reference generator of FIG. **5** at a supply voltage level of 1.2V.

[0181] FIG. **12** is a schematic diagram of one embodiment of a mobile device **800**. The mobile device **800** includes a baseband system **801**, a transceiver **802**, a front end system **803**, antennas **804**, a power management system **805**, a memory **806**, a user interface **807**, and a battery **808**.

[0182] The mobile device **800** can be used communicate using a wide variety of communications technologies, including, but not limited to, 2G, 3G, 4G (including LTE, LTE-Advanced, and LTE-Advanced Pro), 5G NR, WLAN (for instance, WiFi), WPAN (for instance, Bluetooth and ZigBee), WMAN (for instance, WiMax), and/or GPS technologies.

[0183] The transceiver **802** generates RF signals for transmission and processes incoming RF signals received from the antennas **804**. It will be understood that various functionalities associated with the transmission and receiving of RF signals can be achieved by one or more components that are collectively represented in FIG. **12** as the transceiver **802**. In one example, separate components (for instance, separate circuits or dies) can be provided for handling certain types of RF signals.

[0184] The front end system **803** aids is conditioning signals transmitted to and/or received from the antennas **804**. In the illustrated embodiment, the front end system **803** includes a bandgap reference generator **810**, power amplifiers (PAs) **811**, low noise amplifiers (LNAs) **812**, filters **813**, switches **814**, and signal splitting/combining circuitry **815**. However, other implementations are possible.

[0185] For example, the front end system **803** can provide a number of functionalities, including, but not limited to, amplifying signals for transmission, amplifying received signals, filtering signals, switching between different bands, switching between different power modes, switching between transmission and receiving modes, duplexing of signals, multiplexing of signals (for instance, diplexing or triplexing), or some combination thereof.

[0186] The mobile device system **800** illustrates one example application of a bandgap reference generator implemented in accordance with the teachings herein. However, the bandgap reference generators herein can be used in a wide variety of applications.

[0187] In certain implementations, the mobile device **800** supports carrier aggregation, thereby providing flexibility to increase peak data rates. Carrier aggregation can be used for both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD), and may be used to aggregate a plurality of carriers or channels. Carrier aggregation includes contiguous aggregation, in which contiguous carriers within the same operating frequency band are aggregated. Carrier aggregation can also be non-contiguous, and can include carriers separated in frequency within a common band or in different bands.

[0188] The antennas **804** can include antennas used for a wide variety of types of communications. For example, the antennas **804** can include antennas for transmitting and/or receiving signals associated with a wide variety of frequencies and communications standards.

[0189] In certain implementations, the antennas **804** support MIMO communications and/or switched diversity communications. For example, MIMO communications use multiple antennas for communicating multiple data streams over a single radio frequency channel. MIMO communications benefit from higher signal to noise ratio, improved coding, and/or reduced signal interference due to spatial multiplexing differences of the radio environment. Switched diversity refers to communications in which a particular antenna is selected for operation at a particular time. For example, a switch can be used to select a particular antenna from a group of antennas based on a variety of factors, such as an observed bit error rate and/or a signal strength indicator.

[0190] The mobile device **800** can operate with beamforming in certain implementations. For example, the front end system **803** can include amplifiers having controllable gain and phase shifters having controllable phase to provide beam formation and directivity for transmission and/or reception of signals using the antennas **804**. For example, in the context of signal transmission, the amplitude and phases of the transmit signals provided to the antennas **804** are controlled such that radiated signals from the antennas **804** combine using constructive and destructive interference to generate an aggregate transmit signal exhibiting beam-like qualities with more signal strength propagating in a given direction. In the context of signal reception, the amplitude and phases are controlled such that more signal energy is received when the signal is arriving to the antennas **804** from a particular direction. In certain implementations, the antennas **804** include one or more arrays of antenna elements to enhance beamforming.

[0191] The baseband system **801** is coupled to the user interface **807** to facilitate processing of various user input and output (I/O), such as voice and data. The baseband system **801** provides the transceiver **802** with digital representations of transmit signals, which the transceiver **802** processes to generate RF signals for transmission. The baseband system **801** also processes digital representations of received signals provided by the transceiver **802**. As shown in FIG. **12**, the baseband system **801** is coupled to the memory **806** of facilitate operation of the mobile device **800**.

[0192] The memory **806** can be used for a wide variety of purposes, such as storing data and/or instructions to facilitate the operation of the mobile device **800** and/or to provide storage of user information.

[0193] The power management system **805** provides a number of power management functions of the mobile device **800**. In certain implementations, the power management system **805** includes a PA supply control circuit that controls the supply voltages of the power amplifiers **811**. For example, the power management system **805** can be configured to change the supply voltage(s) provided to one or more of the power amplifiers **811** to improve efficiency, such as power added efficiency (PAE).

[0194] As shown in FIG. **12**, the power management system **805** receives a battery voltage from the battery **808**. The battery **808** can be any suitable battery for use in the mobile device **800**, including, for example, a lithium-ion battery.

[0195] FIG. **13** is a schematic diagram of a power amplifier system **860** according to one embodiment. The illustrated power amplifier system **860** includes a bandgap reference generator **810**, a baseband processor **841**, a transmitter/observation receiver **842**, a power amplifier (PA) **843**, a directional coupler **844**, front-end circuitry **845**, an antenna **846**, a PA bias control circuit **847**, and a PA supply control circuit **848**. The transmitter/observation receiver **842** includes an I/Q modulator **857**, a mixer **858**, and an analog-to-digital converter (ADC) **859**. In certain implementations, the transmitter/observation receiver **842** is incorporated into a transceiver.

[0196] The baseband processor **841** can be used to generate an in-phase (I) signal and a quadrature-phase (Q) signal, which can be used to represent a sinusoidal wave or signal of a desired amplitude, frequency, and phase. For example, the I signal can be used to represent an in-phase component of the sinusoidal wave and the Q signal can be used to represent a quadrature-phase component of the sinusoidal wave, which can be an equivalent representation of the sinusoidal wave. In certain implementations, the I and Q signals can be provided to the I/Q modulator **857** in a digital format. The baseband processor **841** can be any suitable processor configured to process a baseband signal. For instance, the baseband processor **841** can include a digital signal processor, a microprocessor, a programmable core, or any combination thereof. Moreover, in some implementations, two or more baseband processors **841** can be included in the power amplifier system **860**.

[0197] The I/Q modulator **857** can be configured to receive the I and Q signals from the baseband processor **841** and to process the I and Q signals to generate an RF signal. For example, the I/Q modulator **857** can include digital-to-analog converters (DACs) configured to convert the I and Q signals into an analog format, mixers for upconverting the I and Q signals to RF, and a signal combiner for combining the upconverted I and Q signals into an RF signal suitable for amplification by the power amplifier **843**. In certain implementations, the I/Q modulator **857** can include one or more filters configured to filter frequency content of signals processed therein.

[0198] The power amplifier **843** can receive the RF signal from the I/Q modulator **857**, and when enabled can provide an amplified RF signal to the antenna **846** via the front-end circuitry **845**.

[0199] The front-end circuitry **845** can be implemented in a wide variety of ways. In one example, the front-end circuitry **845** includes one or more switches, filters, duplexers, multiplexers, and/or other components. In another example, the front-end circuitry **845** is omitted in favor of the power amplifier **843** providing the amplified RF signal directly to the antenna **846**.

[0200] The directional coupler **844** senses an output signal of the power amplifier **823**. Additionally, the sensed output signal from the directional coupler **844** is provided to the mixer **858**, which multiplies the sensed output signal by a reference signal of a controlled frequency. The mixer **858** operates to generate a downshifted signal by downshifting the sensed output signal's frequency content. The downshifted signal can be provided to the ADC **859**, which can convert the downshifted signal to a digital format suitable for processing by the baseband processor **841**. Including a feedback path from the output of the power amplifier **843** to the baseband processor **841** can provide a number of advantages. For example, implementing the baseband processor **841** in this manner can aid in providing power control, compensating for transmitter impairments, and/or in performing digital pre-distortion (DPD). Although one example of a sensing path for a power amplifier is shown, other implementations are possible.

[0201] The PA supply control circuit **848** receives a power control signal from the baseband processor **841**, and controls supply voltages of the power amplifier **843**. In the illustrated configuration, the PA supply control circuit **848** generates a first supply voltage V_{CC1} for powering an input stage of the power amplifier **843** and a second supply voltage V_{CC2} for powering an output stage of the power amplifier **843**. The PA supply control circuit **848** can control the voltage level of the first supply voltage V_{CC1} and/or the second supply voltage V_{CC2} to enhance the power amplifier system's PAE.

[0202] The PA supply control circuit **848** can employ various power management techniques to change the voltage level of one or more of the supply voltages over time to improve the power amplifier's power added efficiency (PAE), thereby reducing power dissipation.

[0203] One technique for improving efficiency of a power amplifier is average power tracking (APT), in which a DC-to-DC converter is used to generate a supply voltage for a power amplifier based on the power amplifier's average output power. Another technique for improving efficiency of a power amplifier is envelope tracking (ET), in which a supply voltage of the power amplifier is controlled in relation to the envelope of the RF signal. Thus, when a voltage level of the envelope of the RF signal increases the voltage level of the power amplifier's supply voltage can be increased. Likewise, when the voltage level of the envelope of the RF signal decreases the voltage level of the power amplifier's supply voltage can be decreased to reduce power consumption.

[0204] In certain configurations, the PA supply control circuit **848** is a multi-mode supply control circuit that can operate in multiple supply control modes including an APT mode and an ET mode. For example, the power control signal from the baseband processor **841** can instruct the PA supply control circuit **848** to operate in a particular supply control mode.

[0205] As shown in FIG. **13**, the PA bias control circuit **847** receives a bias control signal from the baseband processor **841**, and generates bias control signals for the power amplifier **843**. In the illustrated configuration, the bias control circuit **847** generates bias control signals for both an input stage of the power amplifier **843** and an output stage of the power amplifier **843**. However, other implementations are possible.

[0206] In the illustrated embodiment, the bandgap reference generator **810** serves to generate one or more reference voltages for the PA bias control circuit **847** and/or the PA supply control circuit **848**, thereby aiding in biasing and/or powering the power amplifier **843**.

[0207] The power amplifier system **860** illustrates another example application of a bandgap reference generator implemented in accordance with the teachings herein. However, the bandgap reference generators herein can be used in a wide variety of applications.

[0208] FIG. **14**A is a schematic diagram of one embodiment of a packaged module **900**. FIG. **14**B is a schematic diagram of a cross-section of the packaged module **900** of FIG. **14**A taken along the lines **14**B-**14**B.

[0209] The packaged module **900** includes radio frequency components **901**, a semiconductor die **902**, surface mount devices **903**, wirebonds **908**, a package substrate **920**, and an encapsulation structure **940**. The package substrate

920 includes pads **906** formed from conductors disposed therein. Additionally, the semiconductor die **902** includes pins or pads **904**, and the wirebonds **908** have been used to connect the pads **904** of the die **902** to the pads **906** of the package substrate **920**.

[0210] The semiconductor die **902** includes a bandgap reference generator **810** implemented in accordance with one or more features disclosed herein.

[0211] The packaging substrate **920** can be configured to receive a plurality of components such as radio frequency components **901**, the semiconductor die **902** and the surface mount devices **903**, which can include, for example, surface mount capacitors and/or inductors. In one implementation, the radio frequency components **901** include integrated passive devices (IPDs).

[0212] As shown in FIG. **14**B, the packaged module **900** is shown to include a plurality of contact pads **932** disposed on the side of the packaged module **900** opposite the side used to mount the semiconductor die **902**. Configuring the packaged module **900** in this manner can aid in connecting the packaged module **900** to a circuit board, such as a phone board of a mobile device. The example contact pads **932** can be configured to provide radio frequency signals, bias signals, and/or power (for example, a power supply voltage and ground) to the semiconductor die **902** and/or other components. As shown in FIG. **14**B, the electrical connections between the contact pads **932** and the semiconductor die **902** can be facilitated by connections **933** through the package substrate **920**. The connections **933** can represent electrical paths formed through the package substrate **920**, such as connections associated with vias and conductors of a multilayer laminated package substrate.

[0213] In some embodiments, the packaged module **900** can also include one or more packaging structures to, for example, provide protection and/or facilitate handling. Such a packaging structure can include overmold or encapsulation structure **940** formed over the packaging substrate **920** and the components and die(s) disposed thereon.

[0214] It will be understood that although the packaged module **900** is described in the context of electrical connections based on wirebonds, one or more features of the present disclosure can also be implemented in other packaging configurations, including, for example, flip-chip configurations.

Applications

[0215] Some of the embodiments described above have provided examples of bandgap reference generation in connection with wireless communications devices. However, the principles and advantages of the embodiments can be used for any other systems or apparatus that benefit from any of the circuits and systems described herein.

[0216] For example, bandgap reference generators can be included in various electronic devices, including, but not limited to consumer electronic products, parts of the consumer electronic products, electronic test equipment, etc. Example electronic devices include, but are not limited to, a base station, a wireless network access point, a mobile phone (for instance, a smartphone), a tablet, a television, a computer monitor, a computer, a hand-held computer, a personal digital assistant (PDA), a microwave, a refrigerator, an automobile, a stereo system, a disc player, a digital camera, a portable memory chip, a washer, a dryer, a copier, a facsimile machine, a scanner, a multi-functional peripheral device, a wrist watch, a clock, etc. Further, the electronic devices can include unfinished products.

CONCLUSION

[0217] Unless the context clearly requires otherwise, throughout the description and the claims, the words "comprise," "comprising," and the like are to be construed in an inclusive sense, as opposed to an exclusive or exhaustive sense; that is to say, in the sense of "including, but not limited to." The word "coupled", as generally used herein, refers to two or more elements that may be either directly connected, or connected by way of one or more intermediate elements. Likewise, the word "connected", as generally used herein, refers to two or more elements that may be either directly connected, or connected by way of one or more intermediate elements. Additionally, the words "herein," "above," "below," and words of similar import, when used in this application, shall refer to this application as a whole and not to any particular portions of this application. Where the context permits, words in the above Detailed Description using the singular or plural number may also include the plural or singular number respectively. The word "or" in reference to a list of two or more items, that word covers all of the following interpretations of the word: any of the items in the list, all of the items in the list, and any combination of the items in the list.

[0218] Moreover, conditional language used herein, such as, among others, "may," "could," "might," "can," "e.g.," "for example," "such as" and the like, unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain embodiments include, while other embodiments do not include, certain features, elements and/or states. Thus, such conditional language is not generally intended to imply that features, elements and/or states are in any way required for one or more embodiments or that one or more embodiments necessarily include logic for deciding, with or without author input or prompting, whether these features, elements and/or states are included or are to be performed in any particular embodiment.

[0219] The above detailed description of embodiments of the invention is not intended to be exhaustive or to limit the invention to the precise form disclosed above. While specific embodiments of, and examples for, the invention are described above for illustrative purposes, various equivalent modifications are possible within the scope of the invention, as those skilled in the relevant art will recognize. For example, while processes or blocks are presented in a given order, alternative embodiments may perform routines having steps, or employ systems having blocks, in a different order, and some processes or blocks may be deleted, moved, added, subdivided, combined, and/or modified. Each of these processes or blocks may be implemented in a variety of different ways. Also, while processes or blocks are at times shown as being performed in series, these processes or blocks may instead be performed in parallel, or may be performed at different times.

[0220] The teachings of the invention provided herein can be applied to other systems, not necessarily the system described above. The elements and acts of the various embodiments described above can be combined to provide further embodiments.

[0221] While certain embodiments of the inventions have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of the disclosure. Indeed, the novel methods and systems described herein may be embodied in a variety of other forms; furthermore, various omissions, substitutions and changes in the form of the methods and systems described herein may be made without departing from the spirit of the disclosure. The accompanying claims and their equivalents are intended to cover such forms or modifications as would fall within the scope and spirit of the disclosure.

What is claimed is:

1. A bandgap reference generator comprising:

a first voltage bandgap reference circuit configured to generate a first bandgap reference voltage over a first range of a power supply voltage;

a second voltage bandgap reference circuit configured to generate a second bandgap reference voltage over a second range of the power supply voltage that is greater than the first range;

a bandgap selector circuit configured to output a selected bandgap reference voltage by selecting the first bandgap reference voltage or the second bandgap reference voltage based on a voltage level of the power supply voltage, and to output a mode signal indicating the selected bandgap reference voltage; and

a bandgap translator circuit configured to generate an output bandgap reference voltage based on the selected bandgap reference voltage, the bandgap translator circuit configured to operate as a low dropout regulator in a first state of the mode signal, and to operate as a buffer in a second state of the mode signal.

2. The bandgap reference generator of claim **1** wherein the bandgap translator circuit includes a transistor having a drain configured to generate the output bandgap reference voltage, and an amplifier having a first input configured to receive the selected bandgap reference voltage and an output operable to control a gate of the transistor.

3. The bandgap reference generator of claim **2** wherein the bandgap translator circuit further includes a resistor-capacitor compensation circuit electrically connected between the drain of the transistor and the output of the amplifier, the mode signal operable to control an impedance of the resistor-capacitor compensation circuit.

4. The bandgap reference generator of claim **2** wherein the bandgap translator circuit further includes a first feedback resistor electrically connected between a second input of the amplifier and a ground voltage, a second feedback resistor electrically connected between the second input of the amplifier and the drain of the transistor, and a bypass switch electrically connected in parallel with the second feedback resistor and controlled by the mode signal.

5. The bandgap reference generator of claim **1** wherein the buffer has unity gain.

6. The bandgap reference generator of claim **1** wherein the bandgap translator circuit is further configured to output a plurality of reference voltages by scaling the output bandgap reference voltage by a plurality of different scaling factors.

7. The bandgap reference generator of claim **1** wherein the bandgap translator circuit is further configured to generate the output bandgap reference voltage to compensate for a nominal voltage difference between the first bandgap reference voltage and the second bandgap reference voltage.

8. The bandgap reference generator of claim **1** wherein the bandgap selector circuit selects the first bandgap reference voltage or the second bandgap reference voltage based on comparing the voltage level of the power supply voltage to another reference voltage.

9. The bandgap reference generator of claim **8** wherein the another reference voltage is of a lower precision than the first bandgap reference voltage and the second bandgap reference voltage.

10. A method of bandgap voltage generation, the method comprising:

generating a first bandgap reference voltage over a first range of a power supply voltage using a first voltage bandgap reference circuit;

generating a second bandgap reference voltage over a second range of the power supply voltage using a second voltage bandgap reference circuit, the second range greater than the first range;

selecting the first bandgap reference voltage or the second bandgap reference voltage based on a voltage level of the power supply voltage using a bandgap selector circuit, and outputting the selected bandgap reference voltage and a mode signal indicating the selected bandgap reference voltage; and

generating an output bandgap reference voltage based on the selected bandgap reference voltage using a bandgap translator circuit, including operating the bandgap translator circuit as a low dropout regulator in a first state of the mode signal and as a buffer in a second state of the mode signal.

11. The method of claim **10** wherein selecting the first bandgap reference voltage or the second bandgap reference voltage comprises comparing the voltage level of the power supply voltage to another reference voltage.

12. A front end module comprising:

a package substrate; and

a semiconductor die attached to the package substrate, the semiconductor die including a first voltage bandgap reference circuit configured to generate a first bandgap reference voltage over a first range of a power supply voltage, a second voltage bandgap reference circuit configured to generate a second bandgap reference voltage over a second range of the power supply voltage that is greater than the first range, a bandgap selector circuit configured to output a selected bandgap reference voltage by selecting the first bandgap reference voltage or the second bandgap reference voltage based on a voltage level of the power supply voltage and to output a mode signal indicating the selected bandgap reference voltage, and a bandgap translator circuit configured to generate an output bandgap reference voltage based on the selected bandgap reference voltage, the bandgap translator circuit configured to operate as a low dropout regulator in a first state of the mode signal, and to operate as a buffer in a second state of the mode signal.

13. The front end module of claim **12** wherein the bandgap translator circuit includes a transistor having a drain configured to generate the output bandgap reference voltage, and an amplifier having a first input configured to receive the selected bandgap reference voltage and an output operable to control a gate of the transistor.

14. The front end module of claim **13** wherein the bandgap translator circuit further includes a resistor-capacitor compensation circuit electrically connected between the drain of the transistor and the output of the amplifier, the mode signal operable to control an impedance of the resistor-capacitor compensation circuit.

15. The front end module of claim **13** wherein the bandgap translator circuit further includes a first feedback resistor electrically connected between a second input of the amplifier and a ground voltage, a second feedback resistor electrically connected between the second input of the amplifier and the drain of the transistor, and a bypass switch electrically connected in parallel with the second feedback resistor and controlled by the mode signal.

16. The front end module of claim **12** wherein the buffer has unity gain.

17. The front end module of claim **12** wherein the bandgap translator circuit is further configured to output a plurality of reference voltages by scaling the output bandgap reference voltage by a plurality of different scaling factors.

18. The front end module of claim **12** wherein the bandgap translator circuit is further configured to generate the output bandgap reference voltage to compensate for a nominal voltage difference between the first bandgap reference voltage and the second bandgap reference voltage.

19. The front end module of claim **12** wherein the bandgap selector circuit selects the first bandgap reference voltage or the second bandgap reference voltage based on comparing the voltage level of the power supply voltage to another reference voltage.

20. The front end module of claim **19** wherein the another reference voltage is of a lower precision than the first bandgap reference voltage and the second bandgap reference voltage.

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