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Eshrah

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(54) **APPARATUS AND METHODS FOR ELECTRONIC TESTING USING BEAMFORMING INTEGRATED CIRCUITS AS IMPEDANCE TUNERS**

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G01R 27/28 (2006.01)
G01R 31/28 (2006.01)

(52) **U.S. Cl.**

CPC ***H04B 17/0085*** (2013.01); ***G01R 27/28*** (2013.01); ***G01R 31/2822*** (2013.01)

(58) **Field of Classification Search**

CPC H04B 17/0085; G01R 27/28; G01R 31/2822
USPC 455/67.14
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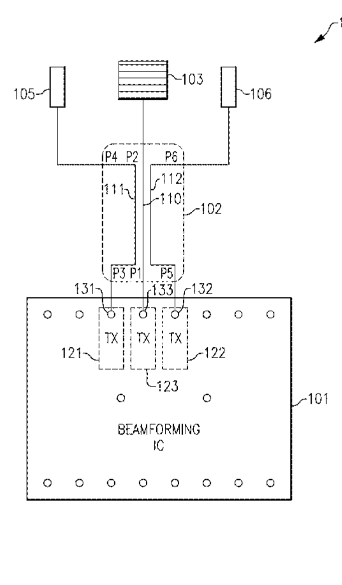
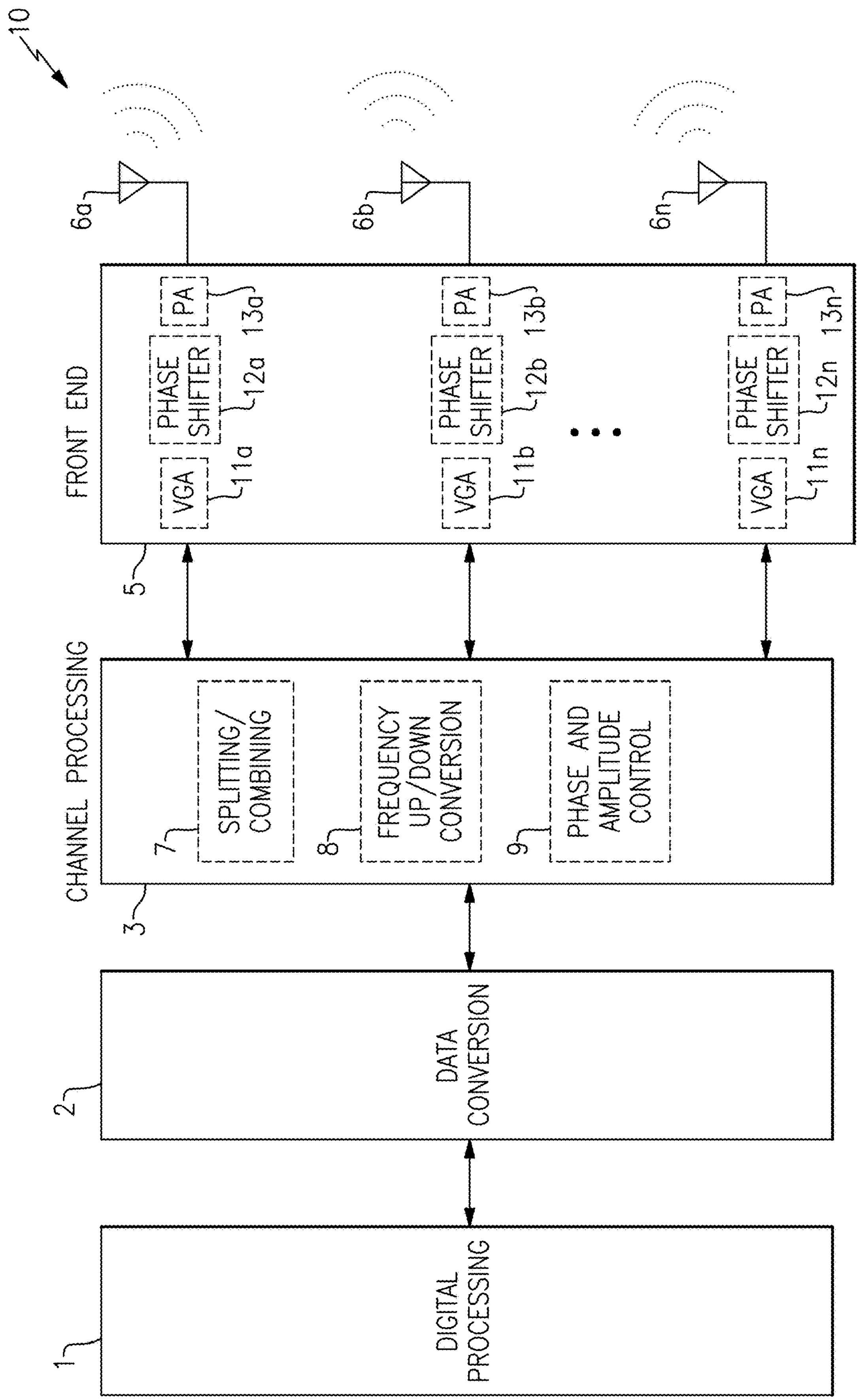
(57) **ABSTRACT**

Apparatus and methods for electronic testing using beamforming integrated circuits (ICs) as impedance tuners are disclosed herein. In certain embodiments, an electronic testing setup for a device-under-test (DUT) includes a radio frequency (RF) coupler including a through line connected to an output of the DUT, a first coupled line coupled to the through line, and a second coupled line coupled to the through line. Additionally, the electronic testing setup includes a beamforming IC including a first transmit channel having an output connected to the first coupled line, and a second transmit channel having an output connected to the second coupled line. A gain and a phase of the first transmit channel and a gain and a phase of the second transmit channel are each controllable to provide impedance tuning at the output of the DUT.

20 Claims, 8 Drawing Sheets

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6a
6b
6n
FRONT END
VGA
PHASE SHIFTER
PA
11a
12a
13a
11b
12b
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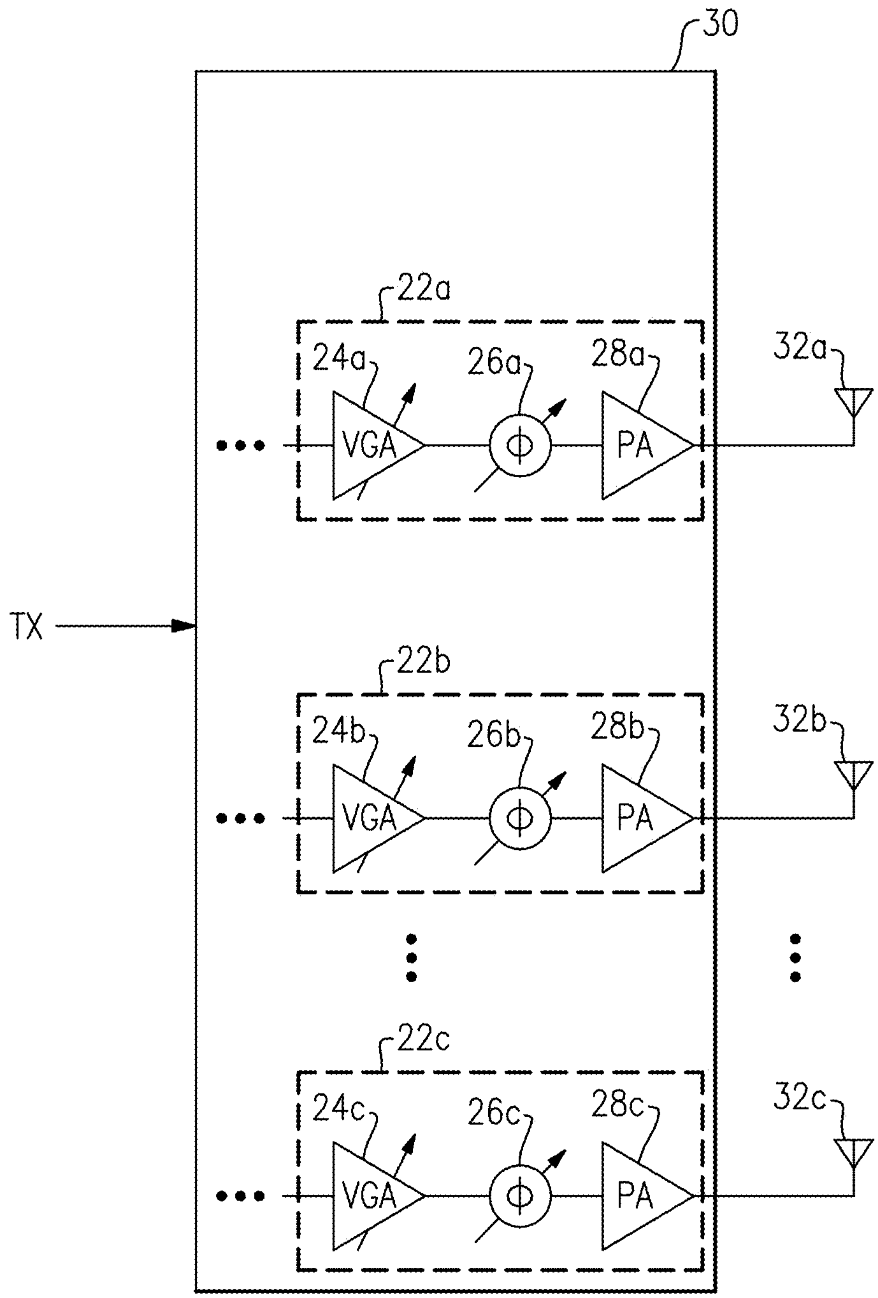
11n
12n
13n
5
CHANNEL PROCESSING
SPLITTING/ COMBINING
FREQUENCY UP/DOWN CONVERSION
PHASE AND AMPLITUDE CONTROL
7
8
9
3
DATA CONVERSION
2
DIGITAL PROCESSING
1

FIG.1


30
22a
24a
26a
28a
32a
VGA
Φ
PA
TX
22b
24b
26b
28b
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PA
22c
24c
26c
28c
32c
VGA
Φ
PA

FIG.2

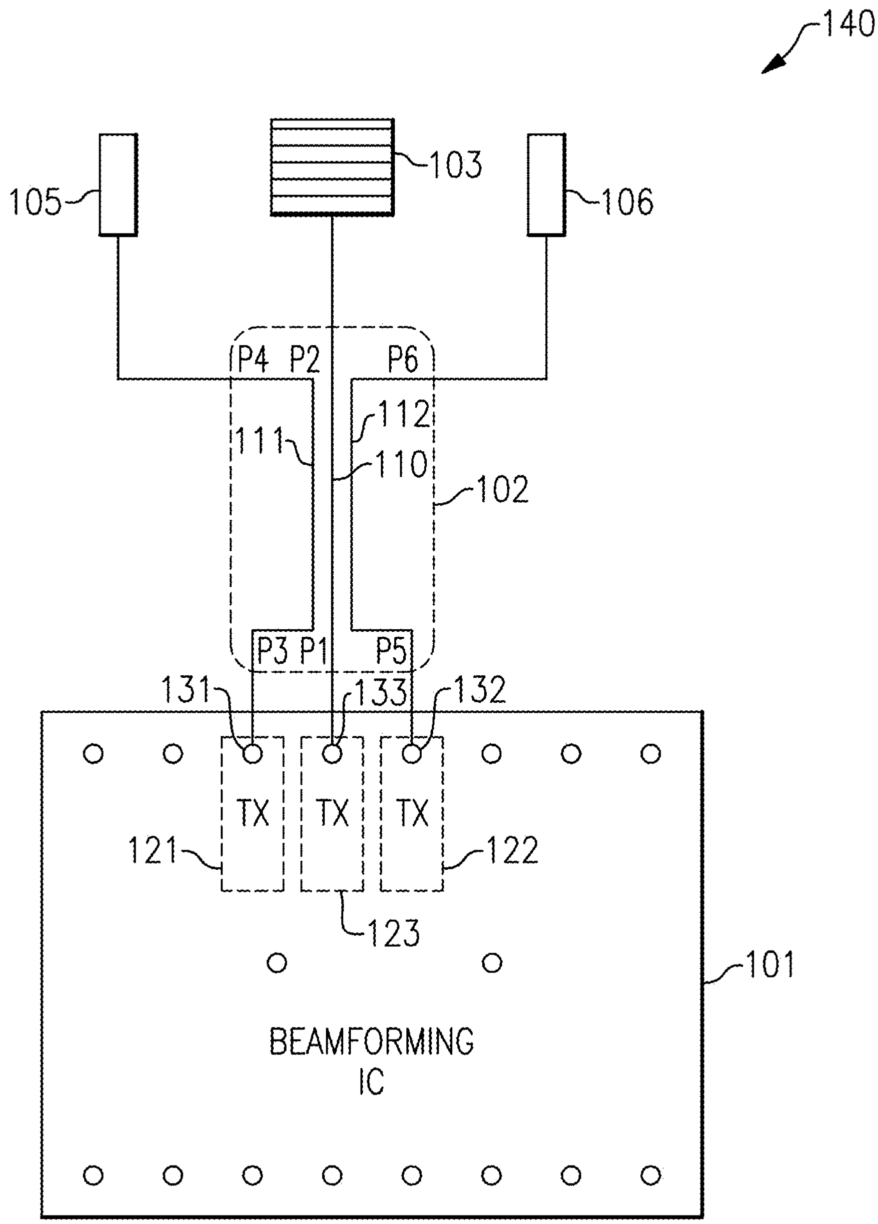

140
105
103
106
P4
P2
P6
111
112
110
102
P3
P1
P5
131
133
132
TX
TX
TX
121
122
123
101
BEAMFORMING
IC

FIG.3A

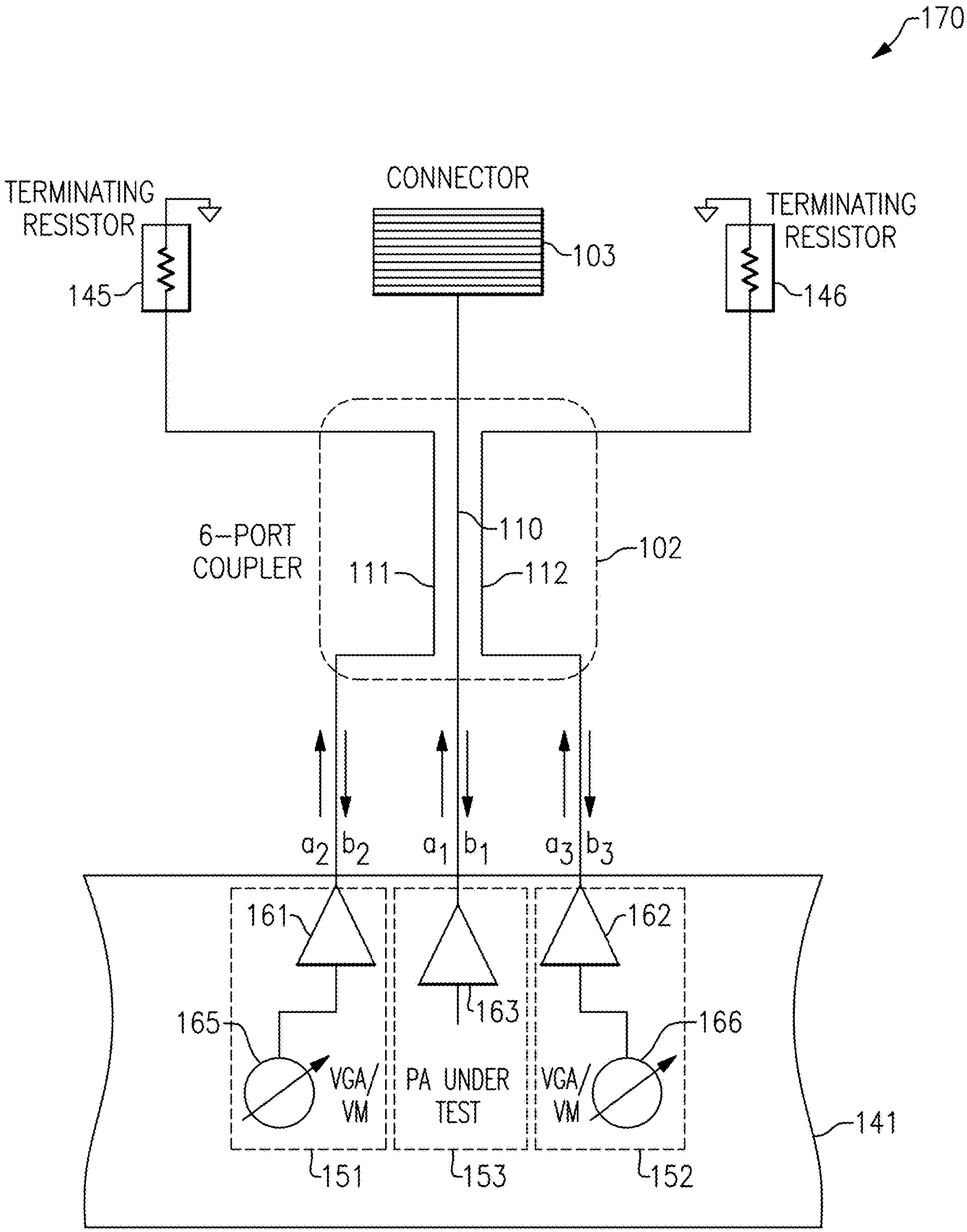

170
TERMINATING RESISTOR
145
CONNECTOR
103
TERMINATING RESISTOR
146
6-PORT COUPLER
111
110
112
102
a_2 b_2 a_1 b_1 a_3 b_3
161
162
163
165
166
VGA/VM
PA UNDER TEST
VGA/VM
151
153
152
141

FIG.3B

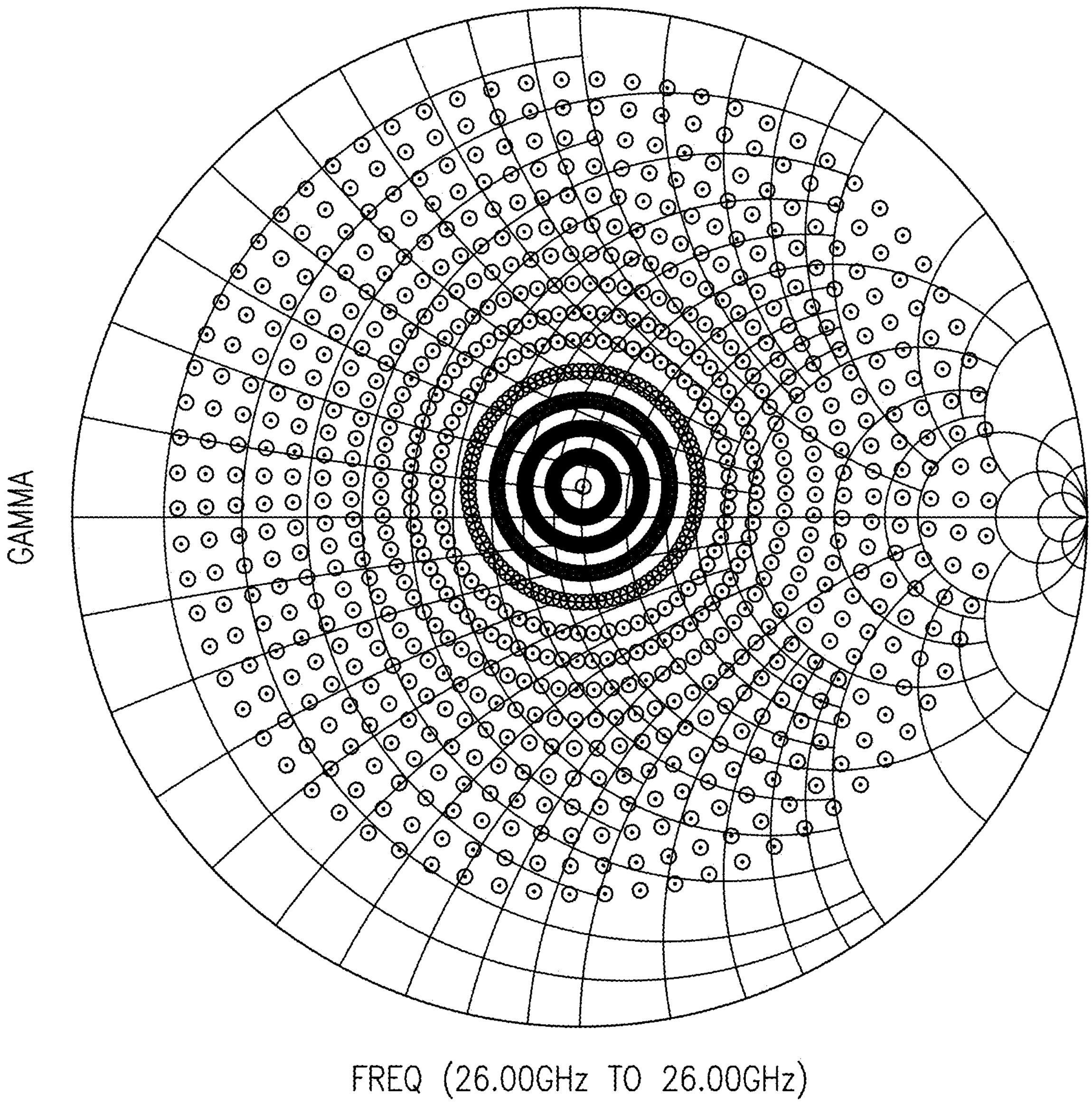
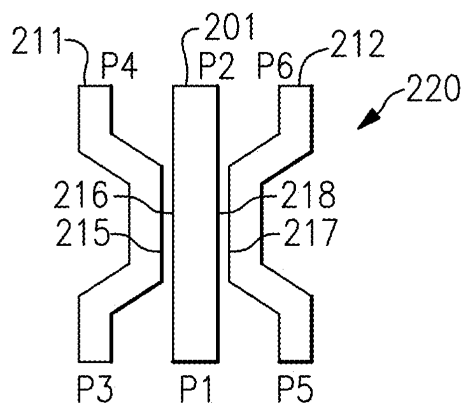


FIG.4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P4
201
P2
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212
220
216
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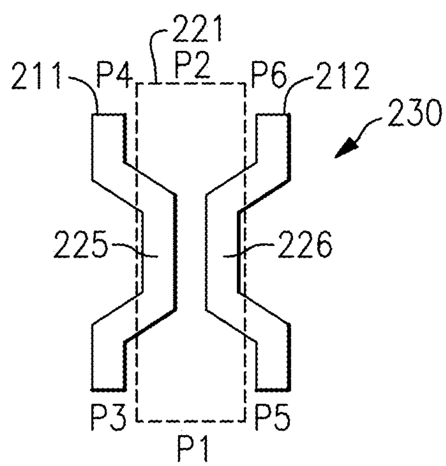
218
217
P3
P1
P5

FIG.5A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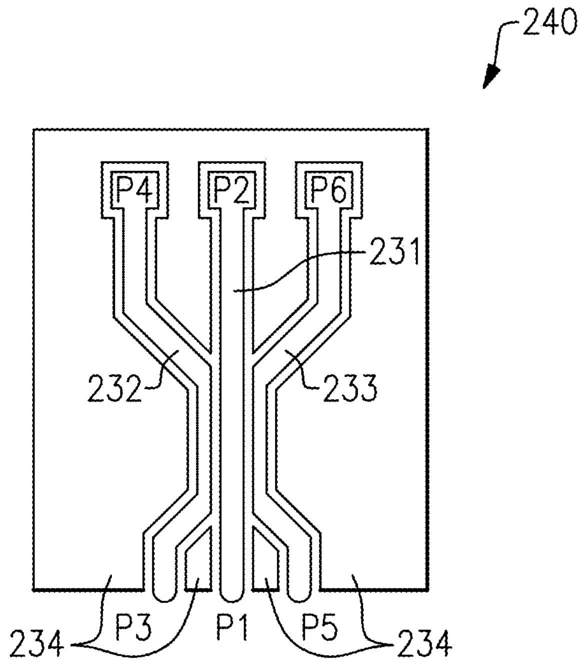
P4
P6
212
230
225
226
P3
P5
P1

FIG.5B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P4
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233
234
P3
P1
P5
234

FIG.5C

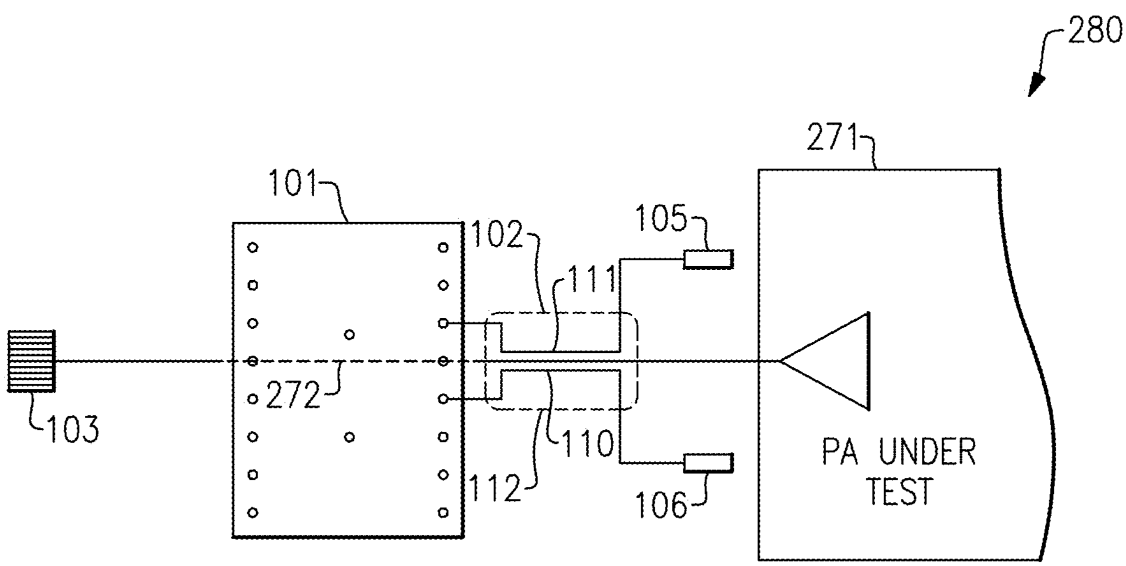
280
271
101
102
105
111
103
272
110
112
106
PA UNDER
TEST

FIG.6

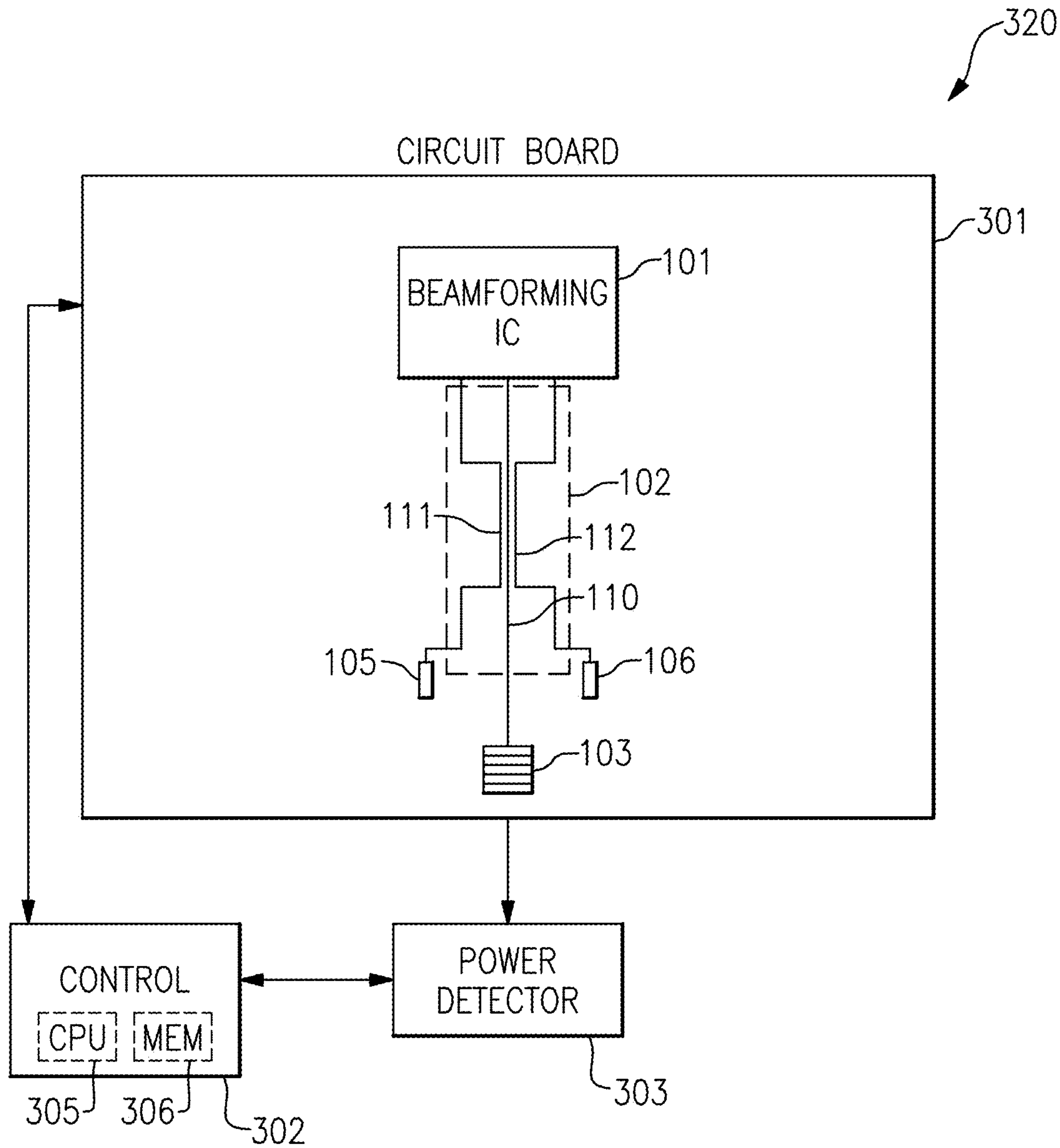
320
CIRCUIT BOARD
301
BEAMFORMING IC
101
102
111
112
110
105
106
103
CONTROL
CPU
MEM
POWER DETECTOR
305
306
302
303

FIG.7

APPARATUS AND METHODS FOR ELECTRONIC TESTING USING BEAMFORMING INTEGRATED CIRCUITS AS IMPEDANCE TUNERS

FIELD OF THE DISCLOSURE

Embodiments of the invention relate to electronics, and more particularly, to electronic testing of radio frequency (RF) components.

BACKGROUND

RF amplifiers can be used in a wide variety of applications to amplify RF signals. Example applications using RF amplifiers include radar, satellite, military, and/or cellular communications.

To provide a performance assessment of an RF amplifier, the RF amplifier can be tested in a variety of ways. For instance, one example of an electronic test for an RF amplifier is load-pull in which an impedance presented to the RF amplifier's output is varied to assess performance under different loading conditions.

SUMMARY OF THE DISCLOSURE

Apparatus and methods for electronic testing using beamforming integrated circuits (ICs) as impedance tuners are disclosed herein. In certain embodiments, an electronic testing setup for a device-under-test (DUT) includes a radio frequency (RF) coupler including a through line connected to an output of the DUT, a first coupled line coupled to the through line, and a second coupled line coupled to the through line. Additionally, the electronic testing setup includes a beamforming IC including a first transmit channel having an output connected to the first coupled line, and a second transmit channel having an output connected to the second coupled line. A gain and a phase of the first transmit channel and a gain and a phase of the second transmit channel are each controllable to provide impedance tuning at the output of the DUT. By implementing the electronic test setup in this manner, a need for external impedance tuners is avoided. Thus, a low cost and compact testing solution is achieved. Moreover, such a testing setup reduces errors arising from losses and/or permits testing at high frequencies such as millimeter wave frequencies and/or frequency range 2 (FR2) of 5G.

In one aspect, an electronic testing setup includes an RF coupler including a through line, a first coupled line coupled to the through line, and a second coupled line coupled to the through line. The through line is configured to receive an RF output signal from an output of a DUT. Additionally, electronic testing setup includes a beamforming IC including a first transmit channel having an output connected to the first coupled line, and a second transmit channel having an output connected to the second coupled line. A gain and a phase of the first transmit channel and a gain and a phase of the second transmit channel are each controllable to provide impedance tuning at the output of the DUT.

In another aspect, a circuit board assembly for electronic testing is provided. The circuit board assembly includes a circuit board including an RF coupler formed thereon, the RF coupler including a through line, a first coupled line coupled to the through line, and a second coupled line coupled to the through line. The through line is configured to receive an RF output signal from an output of a DUT. The circuit board assembly further includes a beamforming IC

attached to the circuit board, the beamforming IC including a first transmit channel having an output connected to the first coupled line, and a second transmit channel having an output connected to the second coupled line. A gain and a phase of the first transmit channel and a gain and a phase of the second transmit channel are each controllable to provide impedance tuning at the output of the DUT.

In another aspect, a method of electronic testing is provided. The method includes providing an RF output signal from an output of a DUT to a through line of an RF coupler, driving a first coupled line of the RF coupler using an output of a first transmit channel of a beamforming IC, and driving a second coupled line of the RF coupler using an output of a second transmit channel of the beamforming IC. The first coupled line is coupled to the through line, and the second coupled line is coupled to the through line. The method further includes providing impedance tuning at the output of the DUT by controlling each of a gain and a phase of the first transmit channel and a gain and a phase of the second transmit channel.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram of one embodiment of a phased array antenna system operating with beamforming.

FIG. **2** is a schematic diagram of one embodiment of a front end system for beamforming a transmit beam.

FIG. **3**A is a schematic diagram of one embodiment of a test setup using transmit channels of a beamforming integrated circuit (IC) as an impedance tuner for another transmit channel of the beamforming IC.

FIG. **3**B is a schematic diagram of another embodiment of a test setup using transmit channels of a beamforming IC as an impedance tuner for another transmit channel of the beamforming IC.

FIG. **4** is a Smith chart depicting one example of testing coverage for a test setup using a beamforming IC as an impedance tuner.

FIG. **5**A is a plan view of a six-port coupler with a coupling arrangement according to one embodiment.

FIG. **5**B is a plan view of a six-port coupler with a coupling arrangement according to another embodiment.

FIG. **5**C is a plan view of a six-port coupler according to another embodiment.

FIG. **6** is a schematic diagram of another embodiment of a test setup using transmit channels of a beamforming IC as an impedance tuner for the power amplifier of another device.

FIG. **7** is a schematic diagram of test equipment according to one embodiment.

DETAILED DESCRIPTION OF EMBODIMENTS

The following detailed description of embodiments presents various descriptions of specific embodiments of the invention. However, the invention can be embodied in a multitude of different ways. In this description, reference is made to the drawings. 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.

Example Phased Array Antenna System and RF Front End for Beamforming

FIG. **1** is a schematic diagram of one embodiment of a phased array antenna system **10** operating with beamforming. The phased array antenna system **10** includes a digital processing circuit **1**, a data conversion circuit **2**, a channel processing circuit **3**, an RF front end **5**, and antennas **6***a*, **6***b*, . . . **6***n*.

Although an example system with three antennas is illustrated, the phased array antenna system **10** can include more or fewer antennas as indicated by the ellipses. Furthermore, in certain implementations, the phased array antenna system **10** is implemented with separate antennas for transmitting and receiving signals. Such antennas can be arrayed, for instance, in a square or rectangular array in some implementations.

The phased array antenna system **10** illustrates one embodiment of an electronic system that can include one or more beamforming ICs. However, beamforming ICs can be used in a wide range of electronics. A phased array antenna system is also referred to herein as an active scanned electronically steered array or beamforming communication system.

As shown in FIG. **1**, the channel processing circuit **3** is connected to antennas **6***a*, **6***b*, . . . **6***n* through the RF front end **5**, which includes variable gain amplifiers (VGAs) **11***a*, **11***b*, . . . **11***n* and phase shifters **12***a*, **12***b*, . . . **12***n* for providing gain control and phase control for the antennas **6***a*, **6***b*, . . . **6***n*, respectively. Additionally, the RF front end **5** includes power amplifiers (PAs) for amplifying RF signals for transmission on the antennas **6***a*, **6***b*, . . . **6***n*. Any number of antennas, VGAs, phase shifters, and/or power amplifiers can be included. Furthermore, the RF front end **5** can include other components not depicted including, but not limited to, low noise amplifiers amplifying RF signals received from the antennas **6***a*, **6***b*, . . . **6***n*.

With continuing reference to FIG. **1**, the digital processing circuit **1** generates digital transmit data for controlling a transmit beam radiated from the antennas **6***a*, **6***b*, . . . **6***n*. The digital processing circuit **1** also can process digital receive data representing a receive beam. In certain implementations, the digital processing circuit **1** includes one or more baseband processors.

As shown in FIG. **1**, the digital processing circuit **1** is connected to the data conversion circuit **2**, which includes digital-to-analog converter (DAC) circuitry for converting digital transmit data to one or more baseband transmit signals and analog-to-digital converter (ADC) circuitry for converting one or more baseband receive signals to digital receive data.

The frequency up/down conversion circuit **8** provides frequency upshifting from baseband to RF and frequency downshifting from RF to baseband, in this embodiment. However, other implementations are possible, such as configurations in which the phased array antenna system **10** operates in part at an intermediate frequency (IF). In certain implementations, the splitting/combining circuit **7** provides splitting to one or more frequency upshifted transmit signals to generate RF signals suitable for processing by the RF front end **5** and subsequent transmission on the antennas **6***a*, **6***b*, . . . **6***n*. Additionally, the splitting/combining circuit **7** combines RF signals received vias the antennas **6***a*, **6***b*, . . . **6***n* and RF front end **5** to generate one or more baseband receive signals for the data conversion circuit **2**.

The channel processing circuit **3** also includes the phase and amplitude control circuit **9** for controlling beamforming operations. For example, the phase and amplitude control circuit **9** controls the amplitudes and phases of RF signals transmitted or received via the antennas **6***a*, **6***b*, . . . **6***n* to provide beamforming. With respect to signal transmission, the RF signal waves radiated from the antennas **6***a*, **6***b*, . . . **6***n* aggregate through constructive and destructive interference to collectively generate a transmit beam having a particular direction. With respect to signal reception, the channel processing circuit **3** generates a receive beam by combining the RF signals received from the antennas **6***a*, **6***b*, . . . **6***n* after amplitude scaling and phase shifting.

Phased array antenna systems are used in a wide variety of applications including, but not limited to, mobile communications, military and defense systems, and/or radar technology.

As shown in FIG. **1**, the RF front end **5** includes VGAs **11***a*, **11***b*, . . . **11***n*, which are used to scale the amplitude of RF signals transmitted or received by the antennas **6***a*, **6***b*, . . . **6***n*, respectively. Additionally, the RF front end **5** includes phase shifters **12***a*, **12***b*, . . . **12***n*, respectively, for phase-shifting the RF signals. For example, in certain implementations the phase and amplitude control circuit **9** generates gain control signals for controlling the amount of gain provided by the VGAs **11***a*, **11***b*, . . . **11***n* and phase control signals for controlling the amount of phase shifting provided by the phase shifters **12***a*, **12***b*, . . . **12***n*.

The phased array antenna system **10** operates to generate a transmit beam and/or receive beam including a main lobe pointed in a desired direction of communication. The phased array antenna system **10** realizes increased signal to noise (SNR) ratio in the direction of the main lobe. The transmit beam and/or receive beam also includes one or more side lobes, which point in different directions than the main lobe and are undesirable.

An accuracy of beam direction of the phased array antenna system **10** is based on a precision in controlling the gain and phases of the RF signals communicated via the antennas **6***a*, **6***b*, . . . **6***n*. For example, when one or more of the RF signals has a large phase error, the beam can be broken and/or pointed in an incorrect direction. Furthermore, the size or magnitude of beam side lobe levels is based on an accuracy in controlling the phases and amplitudes of the RF signals.

Accordingly, it is desirable to tightly control the phase and amplitude of RF signals communicated by the antennas **6***a*, **6***b*, . . . **6***n* to provide robust beamforming operations.

FIG. **2** is a schematic diagram of one embodiment of a front end system **30** for beamforming a transmit beam. The front end system **30** depicts one example of a circuit that can be formed on a semiconductor die to serve as a beamforming IC.

In the illustrated embodiment, the front end system **30** includes a first transmit channel **22***a*, a second transmit channel **22***b*, and a third transmit channel **22***c*. Although three transmit channels are depicted, the front end system **30** can include additional transmit channels as indicated by the ellipses. Furthermore, the front end system **30** can include further components not shown in FIG. **2**, including but not limited to, receive channels for processing RF receive signals.

With continuing reference to FIG. **2**, the first transmit channel **22***a* includes a first VGA **24***a*, a first controllable phase shifter **26***a* (also referred to herein as a vector modulator or VM), and a first power amplifier **28***a* in cascade. Additionally, the second transmit channel **22***b* includes a second VGA **24***b*, a second controllable phase shifter **26***b*, and a second power amplifier **28***b* in cascade. Furthermore, the third transmit channel **22***c* includes a third VGA **24***c*, a third controllable phase shifter **26***c*, and a third power amplifier **28***c* in cascade. Although example components for the transmit channels are depicted, other implementations of the transmit channels are possible. For example, the order of the components can be varied and/or the transmit channels can include additional components.

In the illustrated embodiment, the front end system **30** is connected to an antenna array including a first antenna **32***a*, a second antenna **32***b*, and a third antenna **32***c*. Although three antennas and three transmit channels are depicted, other numbers of antennas and transmit channels are possible.

As shown in FIG. **2**, the front end system **30** receives a transmit signal TX, which can be provided (for instance, using an RF splitter) to each of the transmit channels **22***a*-**22***c*. The transmit channels **22***a*-**22***c* have separately controllable gain and phase to separately adjust the gain and phase of RF output signals provided to the antennas **32***a*-**32***c*. Although not shown in FIG. **2**, the front end system **30** can further be implemented to process RF receive signals from the receive antennas **32***a*-**32***c* (or from separate antennas) to generate a receive signal.

Electronic Testing Using Beamforming ICs as Impedance Tuners

Various RF components undergo electronic testing for a variety of reasons, including characterization. For example, it is important to understand the behavior of the RF component when exposed to varying operating conditions, since the component's behavior can be significantly different under these conditions. A semiconductor die (also referred to herein as an IC) that is undergoing electronic testing is referred to herein as a device-under-test (DUT).

One example of electronic testing for RF components is load-pull, in which the impedance presented to a DUT, typically a power amplifier, is varied to assess performance under different loading conditions. Typical test measurement setups for load-pull use complex impedance tuners to change the impedance seen by the power amplifier to conduct a load-pull analysis of output power. For example, the impedance tuners can correspond to off-board components (external impedance tuners) needing special calibration for proper de-embedding of the impedance seen by the power amplifier. Such external impedance tuners can have a complex and bulky structure to achieve suitable control range of the impedance whether mechanically or electronically.

Conventional load-pull measurement schemes can be unsuitable for a wide range of applications. For instance, load-pull measurements can be difficult to conduct at millimeter wave frequencies due to limitations in precision and/or frequency in the impedance tuners.

Furthermore, even when such impedance tuners are available, the tuners are external and thus calibration of the cables, connectors and routing is prone to many errors.

In applications such as cellular fifth generation (5G) millimeter wave (mmW) phased arrays, the impedance of a given transmit channel of the phased array is varied inherently when the antenna array is phased to different beam positions by virtue of the mutual coupling between the antenna elements of the antenna array.

Thus, beamforming ICs used in phased antenna array modules (PAAM), experience load-pull as the active antenna impedance is varied under beam scan due to the finite isolation between the antenna array elements.

To mimic or emulate such an environment, an intentional coupling mechanism can be implemented on a printed circuit board (PCB) so that the active impedance seen by the power amplifier under test is varied and the load-pull process is conducted. This can be referred to herein as self-impedance tuning.

Apparatus and methods for electronic testing using beamforming ICs as impedance tuners are disclosed herein. In certain embodiments, an electronic testing setup for a DUT includes an RF coupler including a through line connected to an output of the DUT, a first coupled line coupled to the through line, and a second coupled line coupled to the through line. Additionally, the electronic testing setup includes a beamforming IC including a first transmit channel having an output connected to the first coupled line, and a second transmit channel having an output connected to the second coupled line. A gain and a phase of the first transmit channel and a gain and a phase of the second transmit channel are each controllable to provide impedance tuning at the output of the DUT.

Accordingly, the transmit channels of a beamforming IC drive coupled lines of an RF coupler to provide impedance tuning for a DUT. By implementing the electronic test setup in this manner, a need for external impedance tuners is avoided. Thus, a low cost and compact testing solution is achieved. Moreover, such a testing setup reduces errors arising from losses and/or permits testing at high frequencies such as millimeter wave frequencies and/or frequency range 2 (FR2) of 5G.

In certain implementations, the beamforming IC itself is the DUT. Thus, the first and second transmit channels of the beamforming IC can be used to provide impedance tuning to a third transmit channel of the beamforming IC. In certain implementations, each transmit channel of a beamforming IC (which can have any number of transmit channels, for instance 4, 8, or 16 or more) is sequentially tested using two other transmit channels of the beamforming IC, the selection of which changes over time depending on which transmit channel is undergoing test at a particular time. Accordingly, the beamforming IC can participate in its own testing.

In other implementations, the beamforming IC is separate from the DUT, which can correspond to a different RF component (for example, a power amplifier) undergoing test. Accordingly, the teachings herein are applicable both to implementations in which the beamforming IC is used in testing itself as well as to implementations in which the beamforming IC is used in testing other RF components.

FIG. **3**A is a schematic diagram of one embodiment of a test setup **140** using a beamforming IC **101** as an impedance tuner. As shown in FIG. **3**A, the test setup **140** includes the beamforming IC **101**, an RF coupler **102**, a connector **103**, a first termination impedance **105**, and a second termination impedance **106**.

In the illustrated embodiment, the RF coupler **102** includes a through line **110** connected between a first port P**1** and a second port P**2**, a first coupled line **111** connected between a third port P**3** and a fourth port P**4**, and a second coupled line **112** connected between a fifth port P**5** and a sixth port P**6**. The first coupled line **111** is coupled (for instance, magnetically or electromagnetically coupled) to the through line **110**. Likewise, the second coupled line **112** is coupled (for instance, magnetically or electromagnetically coupled) to the through line **110**.

In certain implementations, the RF coupler **102** is formed on a circuit board, such as an evaluation board fabricated using printed circuit board (PCB) technology. Additionally, the beamforming IC **101**, the connector **103**, and/or the termination impedances **105**-**106** can be attached to the circuit board.

As shown in FIG. **3**A, the beamforming IC **101** includes a first transmit channel **121**, a second transmit channel **122**, and a third transmit channel **123**. The beamforming IC **101** further includes various pins or pads including a first pin **131** driven by an output of the first transmit channel **121**, a second pin **132** driven by an output of the second transmit channel **122**, and a third pin **133** driven by an output of the third transmit channel **123**. Although only certain pins and circuits of the beamforming IC **101** are depicted, the beamforming IC **101** can include a number of other pins, circuits, and other structures which are not depicted in FIG. **3**A for clarity of the figure.

With continuing reference to FIG. **3**A, the through line **110** of the RF coupler **102** connects the output of the third transmit channel **123** of the beamforming IC **101** to the connector **103**, which in turn can connect to a desired component such as a power detector. Additionally, the first coupled line **111** of the RF coupler **102** connects the output of the first transmit channel **121** of the beamforming IC **101** to the first termination impedance **105** (for instance, a resistor), while the second coupled line **112** of the RF coupler **102** connects the output of the second transmit channel **122** of the beamforming IC **101** to the second termination impedance **106** (for instance, a resistor).

A gain and a phase of the first transmit channel **121** and a gain and a phase of the second transmit channel **122** are each controllable to provide impedance tuning at the output of the third transmit channel **123**. In the illustrated embodiment, the beamforming IC **101** corresponds not only to the impedance tuner for electronic testing (for example, load-pull testing), but also is the DUT. In particular, the first transmit channel **121** and the second transmit channel **122** of the beamforming IC **101** are used to provide impedance tuning to the output of the third transmit channel **123**.

FIG. **3**B is a schematic diagram of another embodiment of a test setup **170** using a beamforming IC **141** as an impedance tuner. As shown in FIG. **3**B, the test setup **170** includes the beamforming IC **141**, an RF coupler **102**, a connector **103**, a first termination resistor **145**, and a second termination resistor **146**.

The test setup **170** of FIG. **3**B is similar to the test setup **140** of FIG. **3**A, except that the test setup **170** depicts specific implementations of certain components shown in FIG. **3**A.

For example, the beamforming IC **141** of FIG. **3**B includes a first transmit channel **151** including a first VGA/VM **165** and a first power amplifier **161** in cascade, a second transmit channel **152** including a second VGA/VM **166** and a second power amplifier **162** in cascade, and a third transmit channel **153** including a third power amplifier **163** under test. Additionally, the impedance presented to the third power amplifier **163** is tuned for testing by the first power amplifier **161** driving the first coupled line **111** (which is terminated by the first resistor **145** connected to ground) and the second power amplifier **162** driving the second coupled line **112** (which is terminated by the second resistor **146** connected to ground).

Accordingly, the phases and/or gains of the signals outputted by the first transmit channel **151** and the second transmit channel **152** are varied to present the desired impedances at the output of the power amplifier **163** under test.

Thus, the beamforming IC **141** is employed as an impedance tuner by varying the gain and phases (for example, of the VGAs and/or VMs) of transmit channels of the beamforming IC. Since these transmit channels are already included as part of the beamforming IC, more compact testing is achieved relative to a configuration using an external impedance tuner. For example, such external impedance tuners are bulky and expensive.

FIG. **3**B has also been annotated to show a_1 and b_1 coefficients for power amplifier **163**, a_2 and b_2 coefficients for power amplifier **161**, and a_3 and b_3 coefficients for power amplifier **162**.

Using an S-parameter matrix to model the circuit, the reflection coefficient Γ_1 can be expressed as $\Gamma_1=b_1/a_1=s_{11}+s_{12}\ a_2/a_1+s_{13}\ a_3/a_1$. When $s_{12}=s_{13}$ and $s_{11}=0$, the reflection coefficient can be expressed as $\Gamma_1=s_{12}(a_3+a_2)/a_1$.

Accordingly, from the previous equations it will be appreciated that the magnitude and phase of the reflection coefficient can be varied depending on the relative values of the RF signals launched by the transmit channels **151**-**152** and the coupling coefficient of the RF coupler **102**.

FIG. **4** is a Smith chart depicting one example of testing coverage for a test setup using a beamforming IC as an impedance tuner. The Smith chart depicts sample results at 26 GHz for one implementation of the test setup **170** of FIG. **3**B.

To provide impedance tuning, a DUT is loaded with an active load with variable magnitude and phase. In particular, the variable magnitude and phase of the active load allows a sweep of desired power on the Smith chart, with the resulting measurements being used to construct load-pull contours used to characterize the DUT.

As shown in the results of FIG. **5**, sweeping the gains and/or phases of adjacent channels of a beamforming IC results in the depicted coverage of the Smith chart, which robustly spans a range of impedance values suitable for generating load-pull contours.

FIG. **5**A is a plan view of a six-port coupler **220** with a coupling arrangement according to one embodiment. The six-port coupler **220** includes a through line **201** connected between a first port P**1** and a second port P**2**, a first coupled line **211** connected between a third port P**3** and a fourth port P**4**, and a second coupled line **212** connected between a fifth port P**5** and a sixth port P**6**.

In the illustrated embodiment, an edge **215** of the first coupled line **211** is coupled to an edge **216** of the through line **201**, and an edge **217** of the second coupled line **212** is coupled to an edge **218** of the through line **201**. Thus, the coupling arrangement of FIG. **5**A is edge-coupled.

FIG. **5**B is a plan view of a six-port coupler **230** with a coupling arrangement according to another embodiment. The six-port coupler **230** includes a through line **221** connected between a first port P**1** and a second port P**2**, a first coupled line **211** connected between a third port P**3** and a fourth port P**4**, and a second coupled line **212** connected between a fifth port P**5** and a sixth port P**6**. A broadside **225** of the first coupled line **211** is coupled to the through line **221**, and a broadside **226** of the second coupled line **212** is coupled to the through line **221**.

In comparison the coupling arrangement of FIG. **5**A, the six-port coupler **230** of FIG. **5**B uses broadside coupling rather than edge coupling. By providing broadside coupling, greater coverage of the Smith chart can be achieved.

FIG. **5**C is a plan view of a six-port coupler **240** according to another embodiment. The six-port coupler **240** is implemented in a conductive layer of a circuit board that has been patterned to form a through line **231** connected between a first port P**1** and a second port P**2**, a first coupled line **232** connected between a third port P**3** and a fourth port P**4**, a second coupled line **233** connected between a fifth port P**5** and a sixth port P**6**, and shielding conductors **234**, which can be grounded.

The RF couplers herein can be formed in a circuit board, such as an evaluation board formed using PCB technologies.

Although an example with edge-coupling is shown, an RF coupler can also use broadside coupling.

A six-port coupler can be designed to achieve a coupling level suitable for a desired application. For example, a coupling level of the coupler impacts the range of impedances that can be swept on the Smith chart.

An RF coupler, such as the six-port coupler **240** of FIG. **5**C, can be characterized after fabrication to provide calibration and/or correlation of the coupler's S-parameters to simulation.

FIG. **6** is a schematic diagram of another embodiment of a test setup **280** using a beamforming IC **101** as an impedance tuner. As shown in FIG. **6**, the test setup **280** includes the beamforming IC **101**, an RF coupler **102**, a connector **103**, a first termination impedance **105**, a second termination impedance **106**, and a DUT **271** (corresponding to a power amplifier, in this example).

The test setup **280** of FIG. **6** is similar to the test setup **140** of FIG. **3**A, except that in the test setup **280** of FIG. **6** the DUT **271** is separate from (a different RF component than) the beamforming IC **101**.

Accordingly, the beamforming IC **101** is used as an impedance tuner for other DUTs.

As shown in FIG. **6**, the through line **110** of the RF coupler **110** connects the output of the DUT **271** to the connector **103**. In certain implementations, the DUT **271** is also connected to the connector **103** by way of an internal connection **272** of the beamforming IC **101**. However, in other implementations, the internal connection **272** of the beamforming IC **101** is not present. For example, the through line **110** can directly connect the output of the DUT **271** to the connector **103** without the intervening internal connection **272**.

FIG. **7** is a schematic diagram of test equipment **320** according to one embodiment. The test equipment **320** includes a circuit board **301**, a control circuit **302**, and a power detector **303**.

As shown in FIG. **7**, the circuit board **301** includes an RF coupler **102** formed therein. Additionally, a connector **103**, a beamforming IC **101**, a first termination impedance **105**, and a second termination impedance **106** are connected to the circuit board **301**. In the illustrated embodiment, the test equipment **320** is implemented in accordance with the test setup **140** of FIG. **3**A. However, other configurations are possible, such as implementations in which the test equipment is implemented in accordance with the test setup **280** of FIG. **6**.

The circuit board **301** can also be referred to as an evaluation board. In certain implementations, the circuit board **301** is a PCB in which the RF coupler **312** is formed.

In the illustrated embodiment, the power detector **303** is connected to the connector **103** and serves to analyze signals. For example, the power detector **303** can be used to capture load-pull data from the DUT. Additionally, the power detector **303** is connected to the control circuit **302**, which includes a computer processing unit (CPU) **305** and a memory **306**.

In certain implementations, the load-pull data captured by the power detector **303** is stored in the memory **306**, and the processor **305** processes the load-pull data to construct load-pull contours.

The control circuit **302** can be used to provide control data, such as digital control data, to the circuit board **301**. In one example, the control circuit **302** programs the beamforming IC **101** with data instructing the beamforming IC **101** to operate with particular gains and phases for transmit channels, thereby providing impedance tuning.

The memory **306** of the control circuit **302** stores instructions that when executed on the CPU **305** cause the CPU **305** to perform operations for controlling the gain and phase of transmit channels over time to facilitate testing, such as load-pull testing.

Applications

The teachings herein are applicable to testing RF components (for example, RF amplifiers) operating over a wide range of frequencies, including not only RF signals between 100 MHz and 7 GHz, but also to higher frequencies, such as those in the X band (about 7 GHz to 12 GHz), the K_u band (about 12 GHz to 18 GHz), the K band (about 18 GHz to 27 GHz), the K_a band (about 27 GHz to 40 GHz), the V band (about 40 GHz to 75 GHz), and/or the W band (about 75 GHz to 110 GHz). Accordingly, the teachings herein are applicable to a wide range radio frequencies, including microwave frequencies.

Moreover, such RF components can wirelessly communicate RF signals associated with a variety of communication standards, including, but not limited to, Global System for Mobile Communications (GSM), Enhanced Data Rates for GSM Evolution (EDGE), Code Division Multiple Access (CDMA), wideband CDMA (W-CDMA), 3G, Long Term Evolution (LTE), 4G, and/or 5G, as well as other proprietary and non-proprietary communications standards.

CONCLUSION

The foregoing description may refer to elements or features as being "connected". As used herein, unless expressly stated otherwise, "connected" means that one element/feature is directly or indirectly connected to another element/feature, and not necessarily mechanically. Thus, although the various schematics shown in the figures depict example arrangements of elements and components, additional intervening elements, devices, features, or components may be present in an actual embodiment (assuming that the functionality of the depicted circuits is not adversely affected).

While certain embodiments 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 apparatus, 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. For example, while the disclosed embodiments are presented in a given arrangement, alternative embodiments may perform similar functionalities with different components and/or circuit topologies, and some elements may be deleted, moved, added, subdivided, combined, and/or modified. Each of these elements may be implemented in a variety of different ways. Any suitable combination of the elements and acts of the various embodiments described above can be combined to provide further embodiments. Accordingly, the scope of the present invention is defined only by reference to the appended claims.

Although the claims presented here are in single dependency format for filing at the USPTO, it is to be understood that any claim may depend on any preceding claim of the same type except when that is clearly not technically feasible.

What is claimed is:

1. An electronic testing setup comprising:

a radio frequency (RF) coupler including a through line, a first coupled line coupled to the through line, and a second coupled line coupled to the through line, wherein the through line is configured to receive an RF output signal from an output of a device under test (DUT); and

a beamforming integrated circuit (IC) including a first transmit channel having an output connected to the first coupled line, and a second transmit channel having an output connected to the second coupled line, wherein a gain and a phase of the first transmit channel and a gain and a phase of the second transmit channel are each controllable to provide impedance tuning at the output of the DUT.

2. The electronic testing setup of claim **1**, wherein the DUT comprises the beamforming IC.

3. The electronic testing setup of claim **2**, wherein the beamforming IC further comprises a third transmit channel having an output connected to the through line.

4. The electronic testing setup of claim **1**, wherein the first transmit channel includes a first variable gain amplifier a first phase shifter in cascade, and the second transmit channel includes a second variable gain amplifier and a second phase shifter in cascade.

5. The electronic testing setup of claim **1**, further comprising a connector, wherein the through line of the RF coupler is connected between the connector and the output of the DUT.

6. The electronic testing setup of claim **1**, further comprising a first termination impedance and a second termination impedance, wherein the first coupled line is connected between the first termination impedance and the output of the first transmit channel, and the second coupled line is connected between the second termination impedance and the output of the second transmit channel.

7. The electronic testing setup of claim **1**, wherein the DUT includes an RF amplifier configured to drive the output of the DUT, wherein the beamforming IC is configured to provide impedance tuning to perform load-pull measurements on the RF amplifier.

8. The electronic testing setup of claim **1**, wherein the first coupled line and the second coupled line are edge coupled to the through line.

9. The electronic testing setup of claim **1**, wherein the first coupled line and the second coupled line are broadside coupled to the through line.

10. A circuit board assembly for electronic testing, the circuit board assembly comprising:

a circuit board including a radio frequency (RF) coupler formed thereon, the RF coupler including a through line, a first coupled line coupled to the through line, and a second coupled line coupled to the through line, wherein the through line is configured to receive an RF output signal from an output of a device under test (DUT); and

a beamforming integrated circuit (IC) attached to the circuit board, the beamforming IC including a first transmit channel having an output connected to the first coupled line, and a second transmit channel having an output connected to the second coupled line, wherein a gain and a phase of the first transmit channel and a gain and a phase of the second transmit channel are each controllable to provide impedance tuning at the output of the DUT.

11. The circuit board assembly of claim **10**, wherein the DUT comprises the beamforming IC.

12. The circuit board assembly of claim **11**, wherein the beamforming IC further comprises a third transmit channel having an output connected to the through line.

13. The circuit board assembly of claim **10**, wherein the first transmit channel includes a first variable gain amplifier a first phase shifter in cascade, and the second transmit channel includes a second variable gain amplifier and a second phase shifter in cascade.

14. The circuit board assembly of claim **10**, further comprising a connector connected to the circuit board, wherein the through line of the RF coupler is connected between the connector and the output of the DUT.

15. The circuit board assembly of claim **10**, further comprising a first termination impedance and a second termination impedance connected to the circuit board, wherein the first coupled line is connected between the first termination impedance and the output of the first transmit channel, and the second coupled line is connected between the second termination impedance and the output of the second transmit channel.

16. The circuit board assembly of claim **10**, wherein the DUT includes an RF amplifier configured to drive the output of the DUT, wherein the beamforming IC is configured to provide impedance tuning to perform load-pull measurements on the RF amplifier.

17. A method of electronic testing, the method comprising:

providing a radio frequency (RF) output signal from an output of a device under test (DUT) to a through line of an RF coupler;

driving a first coupled line of the RF coupler using an output of a first transmit channel of a beamforming integrated circuit (IC), the first coupled line coupled to the through line;

driving a second coupled line of the RF coupler using an output of a second transmit channel of the beamforming IC, the second coupled line coupled to the through line; and

providing impedance tuning at the output of the DUT by controlling each of a gain and a phase of the first transmit channel and a gain and a phase of the second transmit channel.

18. The method of claim **17**, wherein the DUT comprises the beamforming IC, and wherein providing the RF output signal from the output of the DUT comprises outputting the RF output signal from a third transmit channel of the beamforming IC.

19. The method of claim **17**, wherein the DUT includes an RF amplifier, wherein providing impedance tuning comprises performing load-pull measurements on the RF amplifier.

20. The method of claim **17**, wherein providing impedance tuning comprises controlling a first variable gain amplifier a first phase shifter of the first transmit channel, and controlling a second variable gain amplifier and a second phase shifter of the second transmit channel.

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