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(54) **RECONFIGURABLE MONOLITHICALLY INTEGRATED PHASE-CHANGE ATTENUATOR AND METHODS THEREOF**

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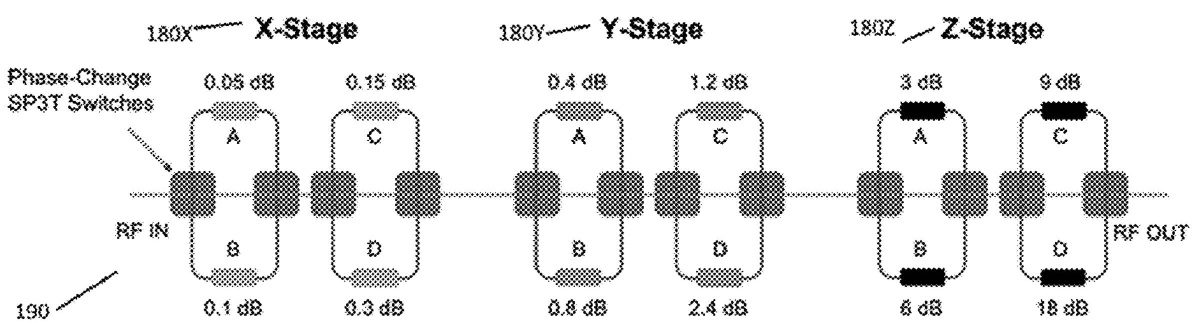
CPC ***H03H 17/0054*** (2013.01); ***H10N 70/231*** (2023.02); *H10N 70/8828* (2023.02)

(57) **ABSTRACT**

A module has two portions, each portion has two units provides an analog-type attenuator-tuning approach having digital control. Each of the units includes an input, an output, three selectable conductive paths, and an input switching element for selectably connecting the unit input to the unit output via one of the three selectable conductive paths. The first and second paths have attenuation elements. The unit output of the first unit of each portion is connected to the unit input of the second unit thereof and the unit output of the via one of the three selectable conductive paths, the unit output of the first unit of each portion is connected to the unit input of the second unit thereof, and the unit output of the second unit of the first portion is connected to the unit input of the first unit of the second portion.



Six crystalline fixed phase-change elements: **X-Stage** A, B, C, D and **Y-Stage** A, B
Six Bridged-T resistor network elements: **Y-Stage** C, D, and **Z-Stage** A, B, C, D

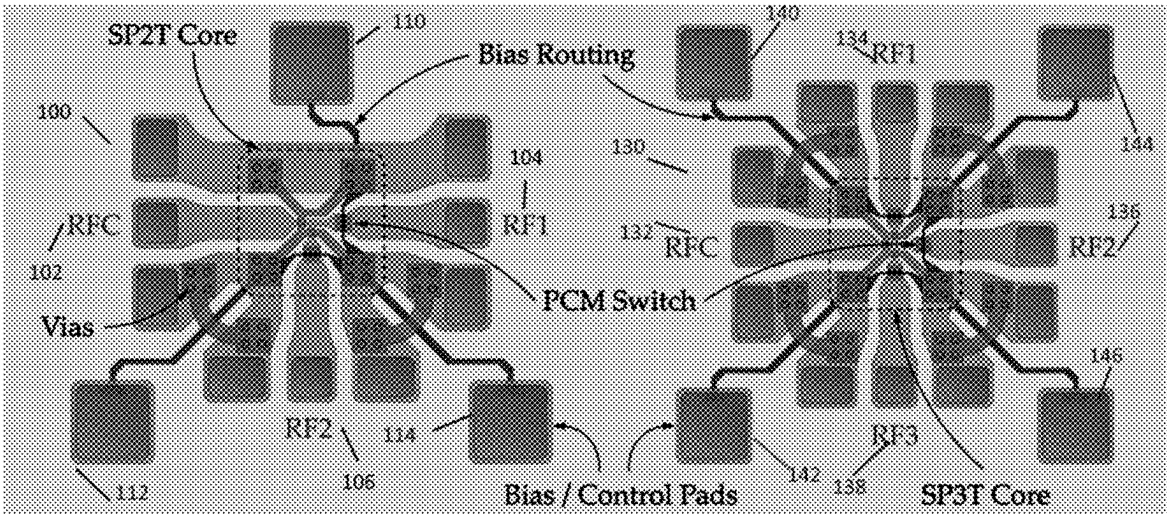
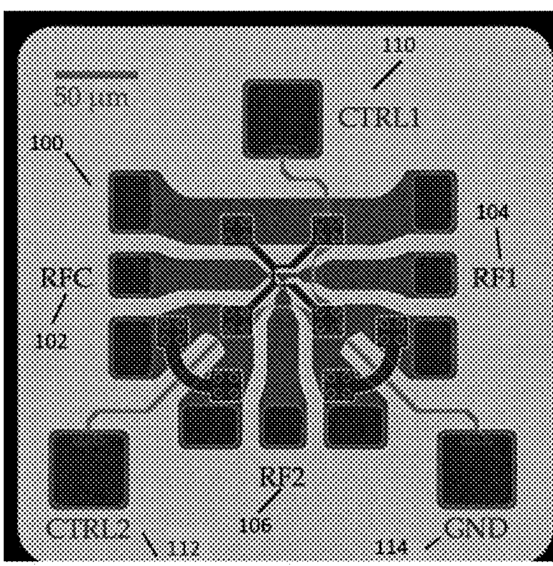


FIG. 1A

FIG. 1B



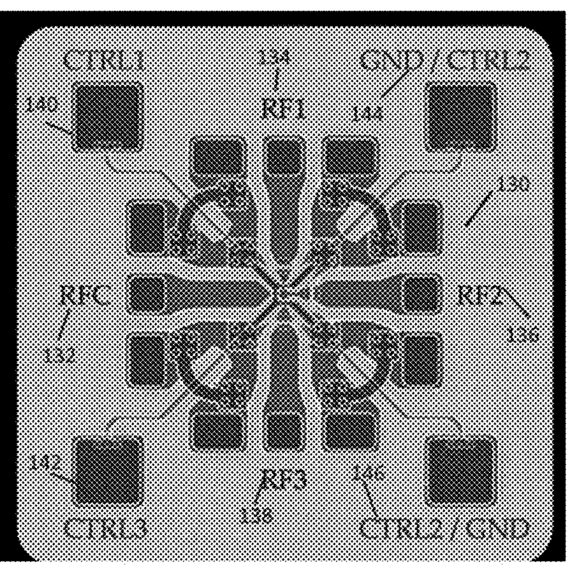


FIG. 2A

FIG. 2B

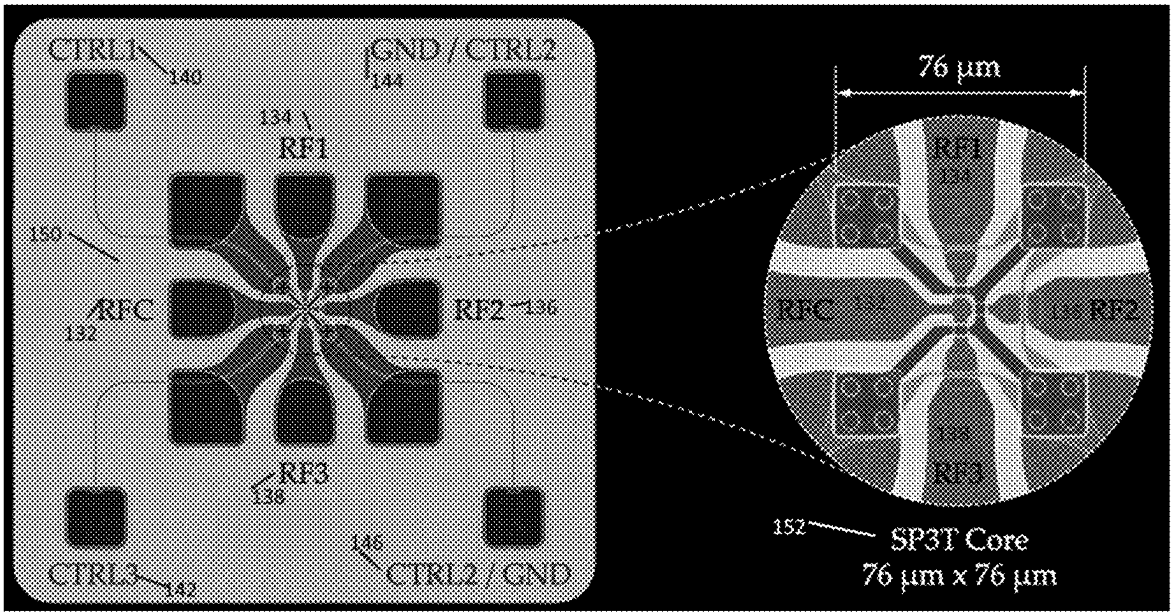

CTRL1
140
GND / CTRL2
144
134
RF1
150
RFC
132
RF2
136
RF3
138
CTRL3
142
146
CTRL2 / GND
76 μm
RF1
RFC
RF2
RF3
152
SP3T Core
76 μm x 76 μm

FIG. 3

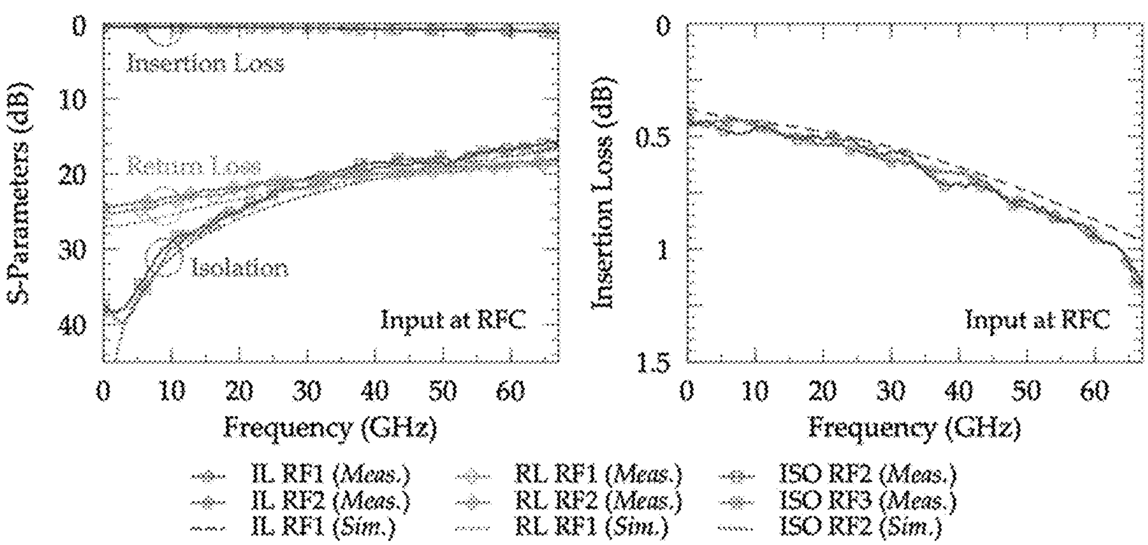

Insertion Loss
Return Loss
Isolation
Input at RFC
S-Parameters (dB)
Frequency (GHz)
Insertion Loss (dB)
Input at RFC
Frequency (GHz)
IL RF1 (Meas.)
IL RF2 (Meas.)
IL RF1 (Sim.)
RL RF1 (Meas.)
RL RF2 (Meas.)
RL RF1 (Sim.)
ISO RF2 (Meas.)
ISO RF3 (Meas.)
ISO RF2 (Sim.)

FIG. 4

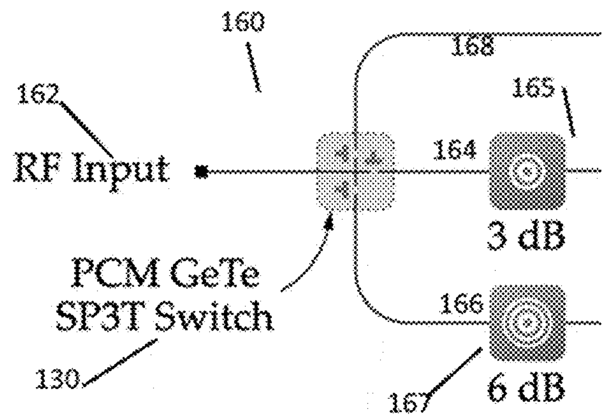

160
168
162
165
RF Input
164
3 dB
PCM GeTe
SP3T Switch
166
130
167
6 dB

FIG. 5

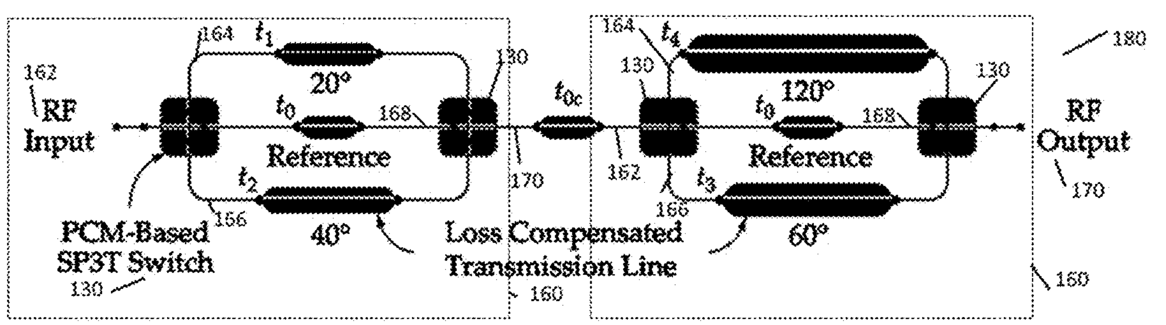

164
t_1
130
t_{0c}
164
t_4
180
162
20°
130
120°
130
RF
Input
t_0
168
t_0
168
RF
Output
Reference
170
162
Reference
t_2
t_3
170
166
166
PCM-Based
SP3T Switch
40°
Loss Compensated
Transmission Line
60°
130
160
160

FIG. 6

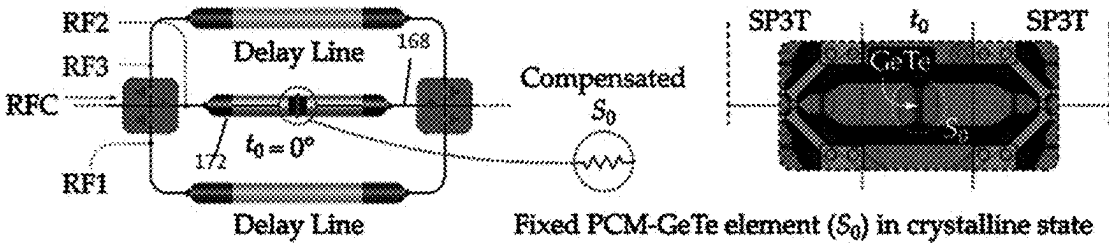

RF2
RF3
RFC
RF1
Delay Line
168
172
$t_0 = 0°$
Delay Line
Compensated
S_0
SP3T
t_0
SP3T
GeTe
S_0
Fixed PCM-GeTe element (S_0) in crystalline state

FIG. 7

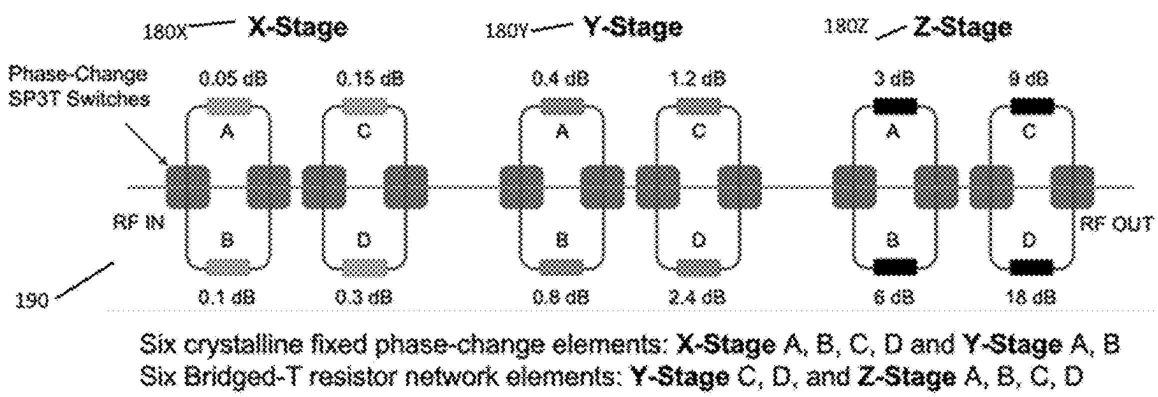
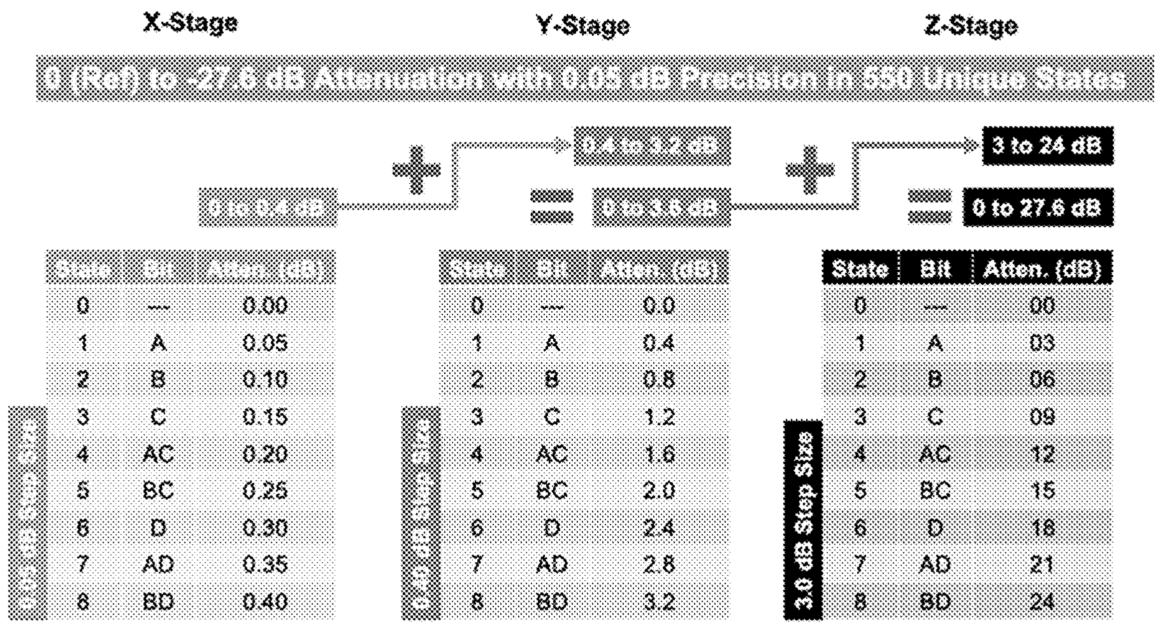

180X X-Stage
180Y Y-Stage
180Z Z-Stage
Phase-Change SP3T Switches
0.05 dB
0.15 dB
0.4 dB
1.2 dB
3 dB
9 dB
A
C
A
C
A
C
RF IN
B
D
B
D
B
D
RF OUT
190
0.1 dB
0.3 dB
0.8 dB
2.4 dB
6 dB
18 dB
Six crystalline fixed phase-change elements: X-Stage A, B, C, D and Y-Stage A, B
Six Bridged-T resistor network elements: Y-Stage C, D, and Z-Stage A, B, C, D

FIG. 8


X-Stage
Y-Stage
Z-Stage
0 (Ref) to -27.6 dB Attenuation with 0.05 dB Precision in 550 Unique States
0 to 0.4 dB
+
0.4 to 3.2 dB
=
0 to 3.6 dB
+
3 to 24 dB
=
0 to 27.6 dB

State	Bit	Atten. (dB)
0	—	0.00
1	A	0.05
2	B	0.10
3	C	0.15
4	AC	0.20
5	BC	0.25
6	D	0.30
7	AD	0.35
8	BD	0.40

0.05 dB Step Size

State	Bit	Atten. (dB)
0	—	0.0
1	A	0.4
2	B	0.8
3	C	1.2
4	AC	1.6
5	BC	2.0
6	D	2.4
7	AD	2.8
8	BD	3.2

0.40 dB Step Size

State	Bit	Atten. (dB)
0	—	00
1	A	03
2	B	06
3	C	09
4	AC	12
5	BC	15
6	D	18
7	AD	21
8	BD	24

3.0 dB Step Size

FIG. 9

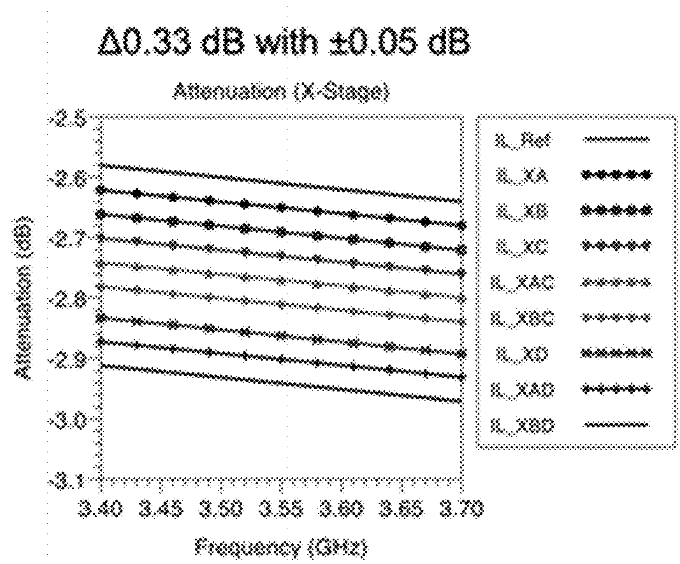

Δ0.33 dB with ±0.05 dB
Attenuation (X-Stage)
Attenuation (dB)
-2.5
-2.6
-2.7
-2.8
-2.9
-3.0
-3.1
3.40
3.45
3.50
3.55
3.60
3.65
3.70
Frequency (GHz)
IL_Ref
IL_XA
IL_XB
IL_XC
IL_XAC
IL_XBC
IL_XD
IL_XAD
IL_XBD

FIG. 10A

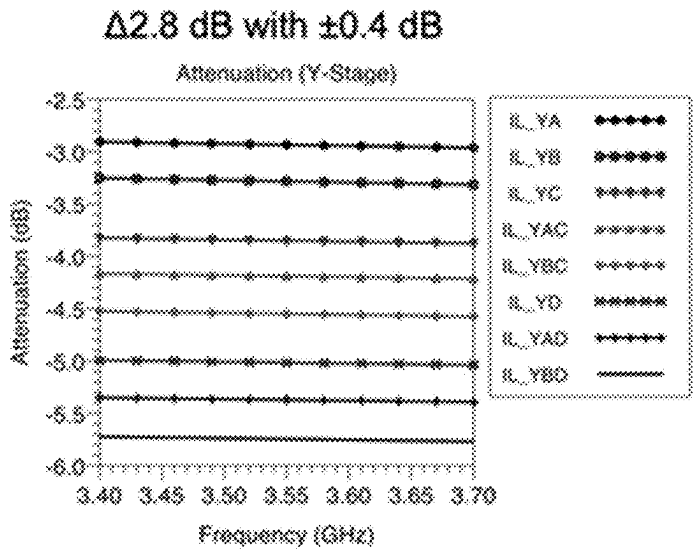


FIG. 10B

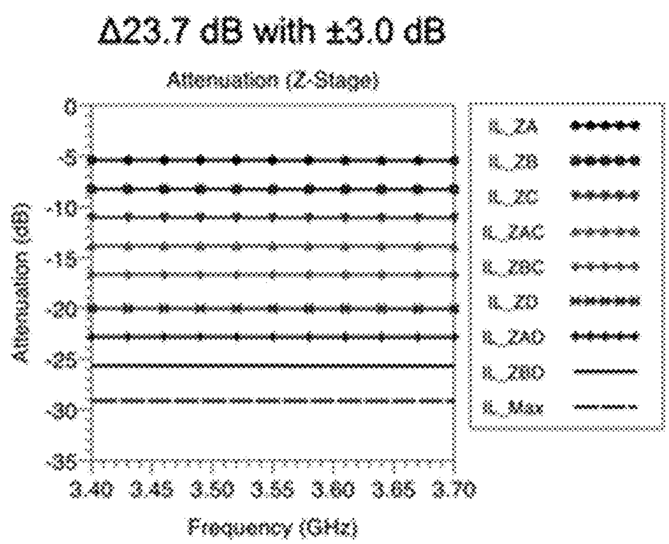


FIG. 10C

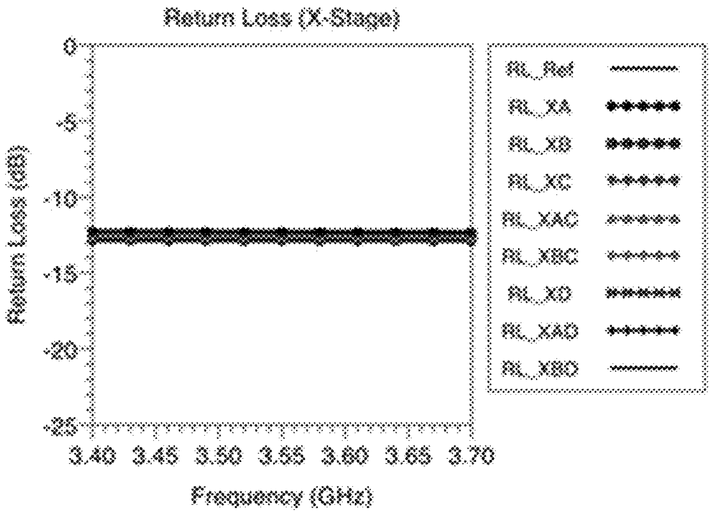


FIG. 10D

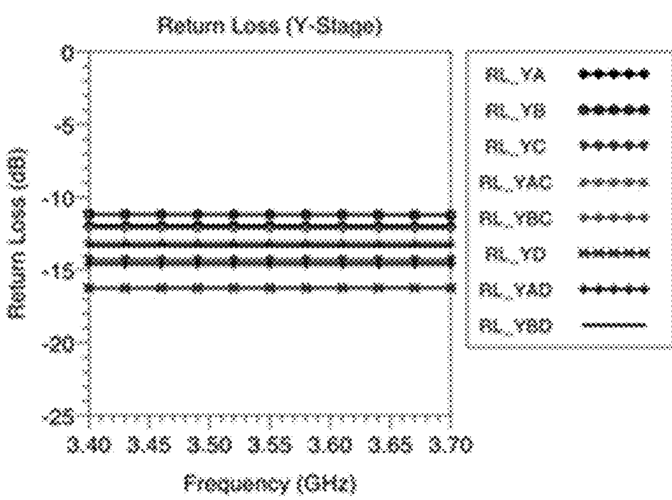


FIG. 10E

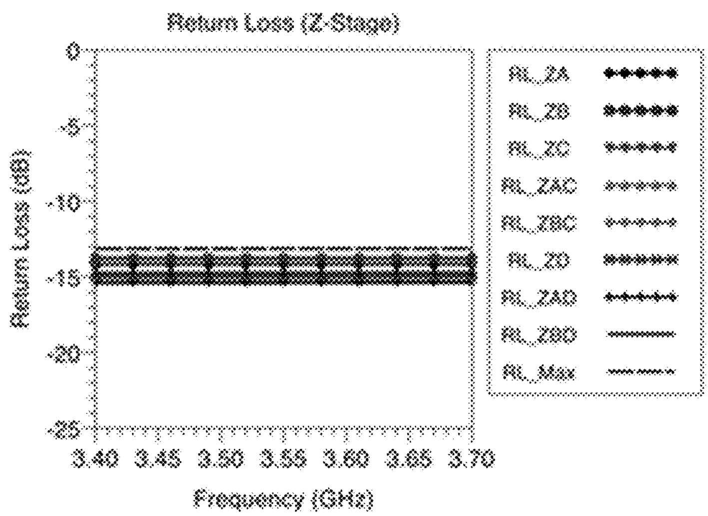


FIG. 10F

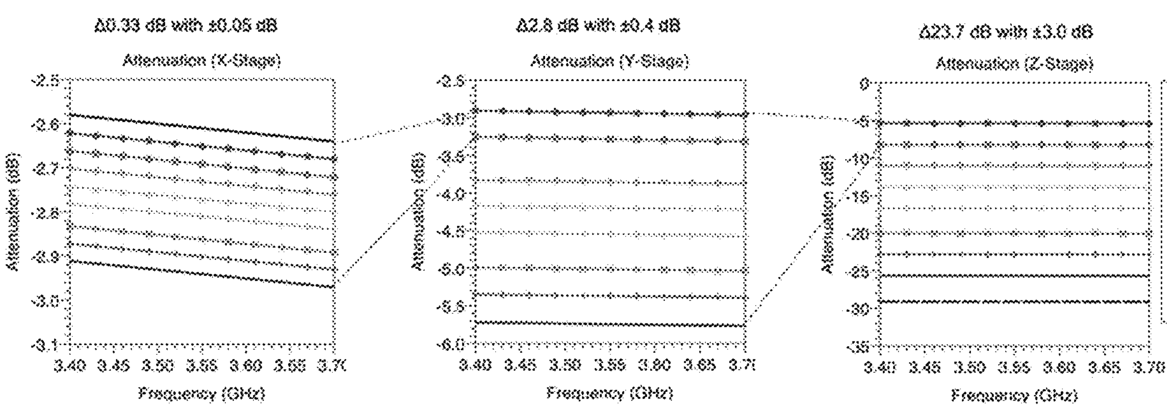


FIG. 11

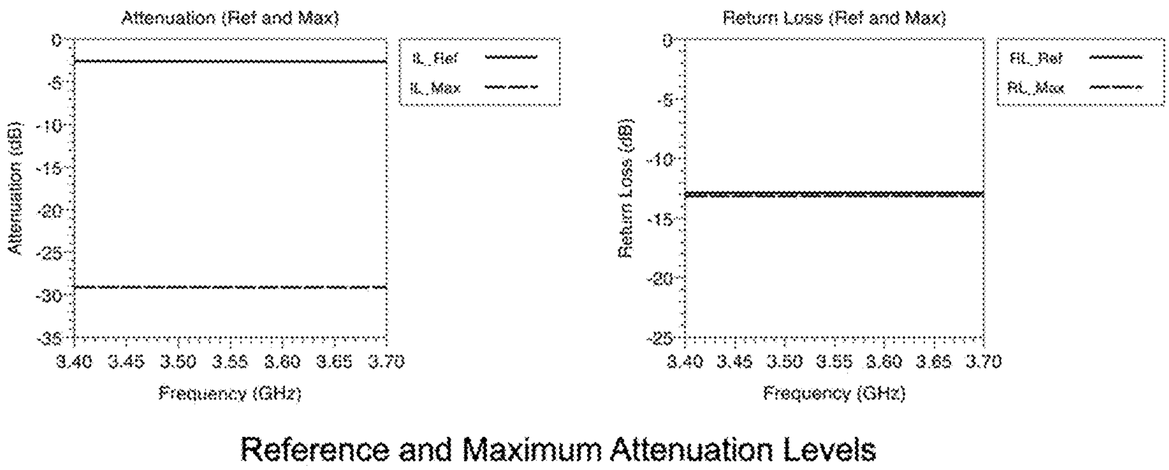

Attenuation (Ref and Max)
IL_Ref
IL_Max
Attenuation (dB)
Frequency (GHz)
Return Loss (Ref and Max)
RL_Ref
RL_Max
Return Loss (dB)
Frequency (GHz)
Reference and Maximum Attenuation Levels

FIG. 12

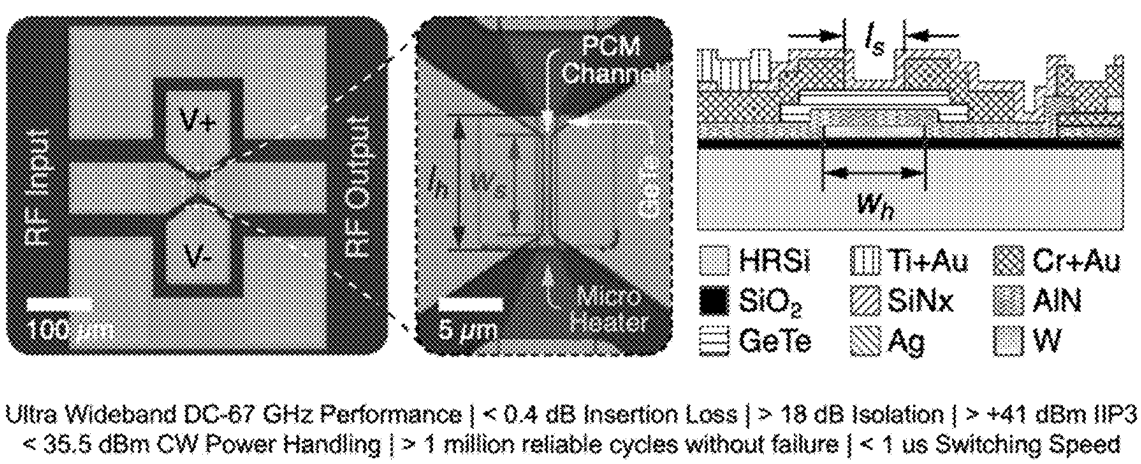

RF Input
V+
V-
RF Output
100 μm
PCM Channel
l_h
w_c
GeTe
Micro Heater
5 μm
l_s
w_h
HRSi
Ti+Au
Cr+Au
SiO_2
SiNx
AlN
GeTe
Ag
W
Ultra Wideband DC-67 GHz Performance | < 0.4 dB Insertion Loss | > 18 dB Isolation | > +41 dBm IIP3
< 35.5 dBm CW Power Handling | > 1 million reliable cycles without failure | < 1 us Switching Speed

FIG. 13

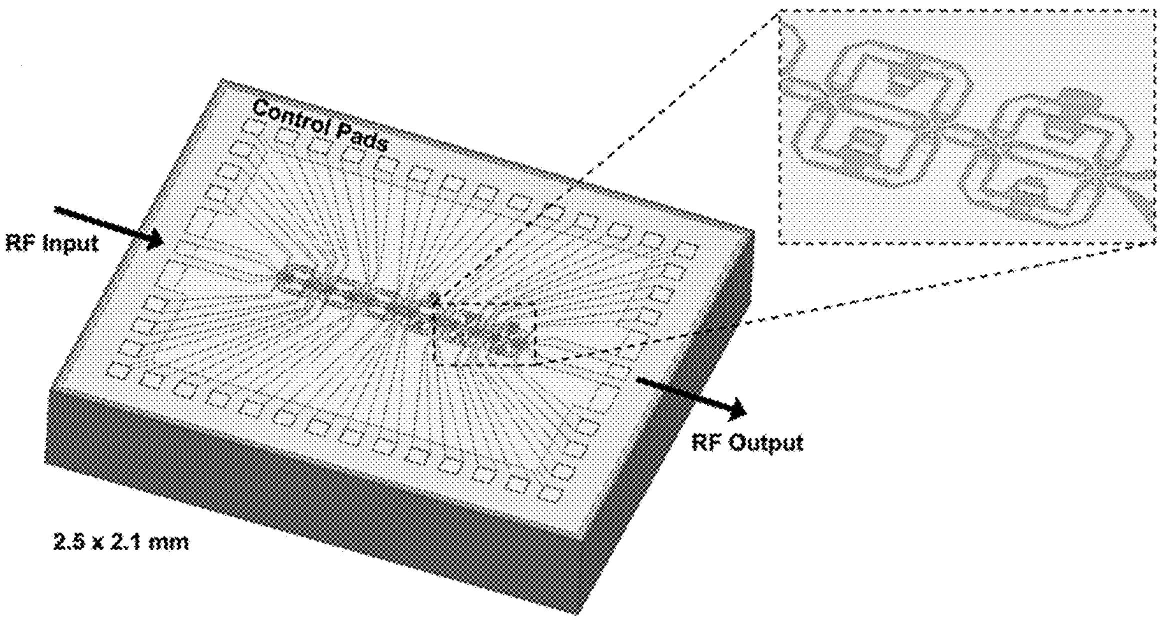

Control Pads
RF Input
RF Output
2.5 x 2.1 mm

FIG. 14

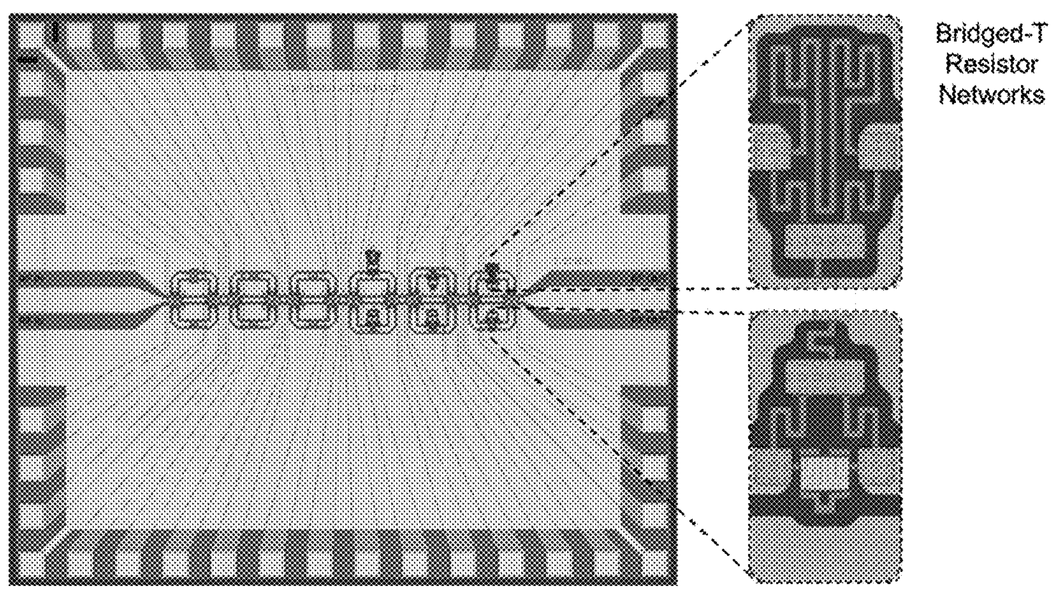

Bridged-T
Resistor
Networks

FIG. 15

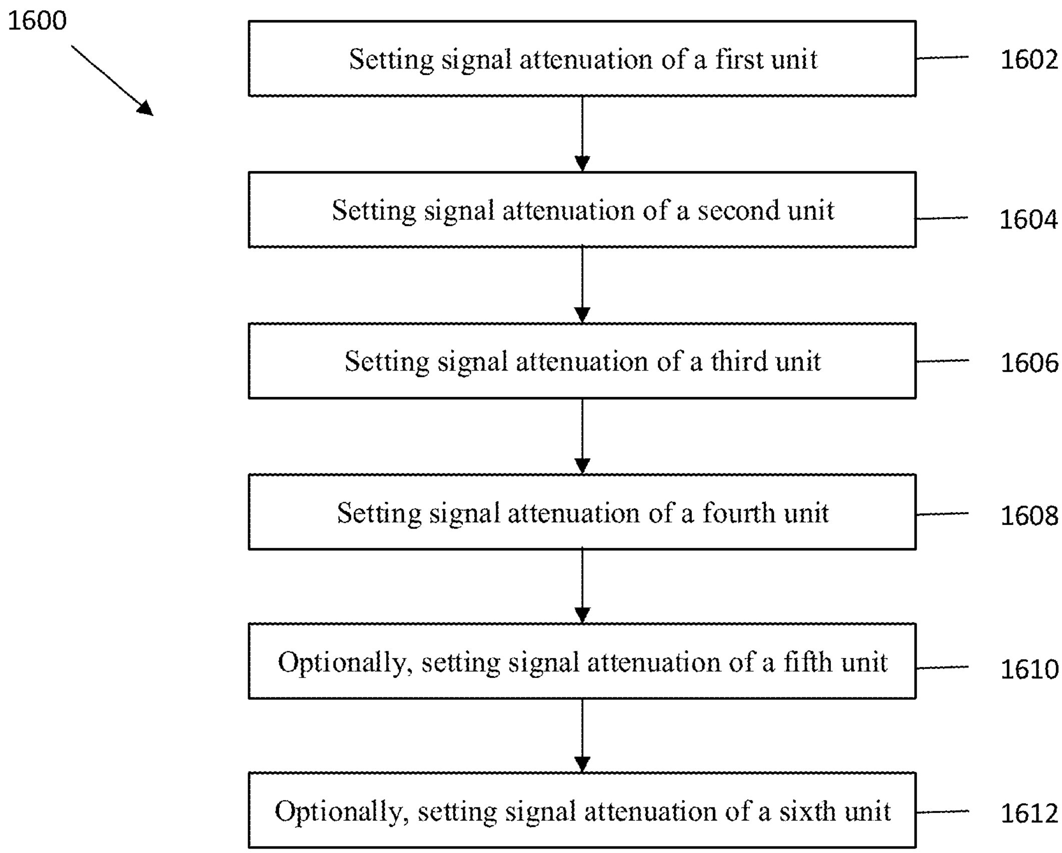

1600
Setting signal attenuation of a first unit
1602
Setting signal attenuation of a second unit
1604
Setting signal attenuation of a third unit
1606
Setting signal attenuation of a fourth unit
1608
Optionally, setting signal attenuation of a fifth unit
1610
Optionally, setting signal attenuation of a sixth unit
1612

FIG. 16

RECONFIGURABLE MONOLITHICALLY INTEGRATED PHASE-CHANGE ATTENUATOR AND METHODS THEREOF

CROSS-REFERENCE TO RELATED APPLICATION

[0001] The present application is a continuation of Patent Cooperation Treaty Application Serial No. PCT/CA2022/051589, entitled "RECONFIGURABLE MONOLITHICALLY INTEGRATED PHASE-CHANGE ATTENUATOR AND METHODS THEREOF," filed on Oct. 26, 2022, the entirety of which is incorporated by reference herein.

TECHNICAL FIELD

[0002] The present disclosure relates generally to signal attenuators for radio frequency systems, and in particular, to digitally-controlled signal attenuators.

BACKGROUND

[0003] Variable reconfigurable radio frequency (RF) systems, including radar systems, vector modulators, full-duplex wireless systems, and automatic gain control amplifiers, require switched attenuators for signal level adjustments. It is important for circuits suitable for such variable reconfigurable RF systems to have the ability to uniformly control signal strength for their application in modern communication systems. However, unlike RF circuits used in receivers, strength-control circuits and attenuators in a pre-distortion or correction loop that are connected to a power amplifier (PA) for transmitter demand power-handling capability, linearity, and reliability for circuits used in modern communication systems. These devices have much more stringent requirements.

SUMMARY

[0004] The present disclosure provides modules and methods for attenuators suitable for applications, including modern communications systems, requiring high linearity, low power consumption, and low temperature dependency. Some embodiments of modules and methods disclosed herein provide attenuators that preserve signal integrity while controlling the signal power. Some embodiments of modules and methods disclosed herein have a high dynamic range, low insertion loss, wide attenuation range, and wide frequency bandwidth.

[0005] According to one aspect of this disclosure, there is provided a module comprising two portions, each portion comprising a first unit and a second unit, each of the units comprising: a unit input; a unit output; a first, a second, and a third selectable conductive path, the first path comprising a first attenuation element and the second path comprising a second attenuation element; and an input switching element for selectably connecting the unit input to the unit output via one of the three selectable conductive paths; wherein the unit output of the first unit of each portion is connected to the unit input of the second unit thereof; and wherein the unit output of the second unit of the first portion is connected to the unit input of the first unit of the second portion.

[0006] In an embodiment, for each unit, signal attenuation of the second attenuation element is greater than signal attenuation of the first attenuation element.

[0007] In an embodiment, for each portion, signal attenuation of the first attenuation element of the second unit is greater than signal attenuation of the second attenuation element of the first unit.

[0008] In an embodiment, signal attenuation of the first attenuation element of the first unit of the second portion is greater than signal attenuation of the second attenuation element of the second unit of the first portion.

[0009] In an embodiment, signal attenuation of: the first attenuation element of the first unit of the first portion is 0.05 decibels (dB), the second attenuation element of the first unit of the first portion is 0.1 dB, the first attenuation element of the second unit of the first portion is 0.15 dB, the second attenuation element of the second unit of the first portion is 0.3 dB, the first attenuation element of the first unit of the second portion is 0.4 dB, the second attenuation element of the first unit of the second portion is 0.8 dB, the first attenuation element of the second unit of the second portion is 1.2 dB, and the second attenuation element of the second unit of the second portion is 2.4 dB.

[0010] In an embodiment, the module comprises a third portion, comprising a first unit and a second unit, each of the units comprising: a unit input; a unit output; a first, a second, and a third selectable conductive path, the first path comprising a first attenuation element and the second path comprising a second attenuation element; and an input switching element for selectably connecting the unit input to the unit output via one of the three selectable conductive paths; wherein the unit output of the first unit is connected to the unit input of the second unit; and wherein the unit output of the second unit of the second portion is connected to the unit input of the first unit of the third portion.

[0011] In an embodiment, for each unit of the third portion, signal attenuation of the second attenuation element is greater than signal attenuation of the first attenuation element.

[0012] In an embodiment, for the third portion, signal attenuation of the first attenuation element of the second unit is greater than signal attenuation of the second attenuation element of the first unit.

[0013] In an embodiment, signal attenuation of the first attenuation element of the first unit of the third portion is greater than signal attenuation of the second attenuation element of the second unit of the second portion.

[0014] In an embodiment, signal attenuation of: the first attenuation element of the first unit of the third portion is 3 dB, the second attenuation element of the first unit of the third portion is 6 dB, the first attenuation element of the second unit of the third portion is 9 dB, and the second attenuation element of the second unit of the third portion is 18 dB.

[0015] In an embodiment, the module comprises one or more additional portions, each additional portion comprising a first unit and a second unit, each of the units comprising: a unit input; a unit output; a first, a second, and a third selectable conductive path, the first path comprising a first attenuation element and the second path comprising a second attenuation element; and an input switching element for selectably connecting the unit input to the unit output via one of the three selectable conductive paths; wherein the unit output of the first unit is connected to the unit input of the second unit.

[0016] In an embodiment, each of the input switching elements is a single pole three-throw switch.

[0017] In an embodiment, each of the input switching elements comprises a phase-change material.

[0018] In an embodiment, the phase-change material comprises germanium telluride.

[0019] In an embodiment, each of the input switching elements comprises four control pads and two shared pads for control and biasing.

[0020] In an embodiment, each of the units further comprises an output switching element connected to the three selectable conductive paths and the unit output for selectably connecting one of the three selectable conductive paths and the unit output.

[0021] In an embodiment, each of the output switching elements is a single pole three-throw switch.

[0022] In an embodiment, each of the output switching elements comprises a phase-change material.

[0023] In an embodiment, the phase-change material comprises germanium telluride.

[0024] In an embodiment, each of the output switching elements comprises four control pads and two shared pads for control and biasing.

[0025] In an embodiment, each of the first attenuation elements and each of the second attenuation elements comprise bridged-T networks.

[0026] In an embodiment, the module comprises one or more amplifiers between each of the portions.

[0027] In an embodiment, the module comprises one or more matching networks between each of the portions.

[0028] According to another aspect of this disclosure, there is provided a method comprising the steps of: setting signal attenuation of a first unit; setting signal attenuation of a second unit; setting signal attenuation of a third unit; and setting signal attenuation of a fourth unit, wherein the first unit, the second, the third unit and the fourth unit are connected in series, and wherein selecting signal attenuation of a unit comprises selecting one of no attenuation, a first signal attenuation and a second signal attenuation thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

[0029] For a more complete understanding of the disclosure, reference is made to the following description and accompanying drawings, in which:

[0030] FIG. **1**A is a schematic of the layout of an embodiment of a single-pole two-throw (SP2T) switch device;

[0031] FIG. **1**B is a schematic of the layout of a single-pole three-throw (SP3T) switch device;

[0032] FIG. **2**A is an illustration of an optical micrograph of the SP2T switch device of FIG. **1**A;

[0033] FIG. **2**B is an illustration of an optical micrograph of the SP3T switch device of FIG. **1**B;

[0034] FIG. **3** is an illustration of an optical micrograph of an embodiment of a SP3T switch device;

[0035] FIG. **4** are graphs illustrating measured and simulated radio frequency performance of an embodiment of a SP3T switch device;

[0036] FIG. **5** is a schematic of a layout of an embodiment of a SP3T switch device connected to an input and three lines including two attenuator bits;

[0037] FIG. **6** is a schematic of an embodiment of a unit;

[0038] FIG. **7** is a schematic of a portion of an embodiment of a unit;

[0039] FIG. **8** is a schematic of an embodiment of a module;

[0040] FIG. **9** is a table illustrating signal attenuation levels of the module of FIG. **8**;

[0041] FIG. **10**A to FIG. **10**F are graphs illustrating attenuation responses and return losses of portions of the module of FIG. **8**;

[0042] FIG. **11** are graphs illustrating attenuation levels of the module of FIG. **8**;

[0043] FIG. **12** are graphs illustrating minimum and maximum signal-attenuation ranges of the module of FIG. **8**;

[0044] FIG. **13** is a schematic illustrating the physical layout of a portion of a module;

[0045] FIG. **14** is a schematic illustrating a chip layout of a module;

[0046] FIG. **15** is an illustration of an optical micrograph of bridged-T resistor networks; and

[0047] FIG. **16** is a flowchart illustrating a method for operating a module.

DETAILED DESCRIPTION

[0048] Although embodiments have been described above with reference to the accompanying drawings, those of skill in the art will appreciate that variations and modifications may be made without departing from the scope thereof as defined by the appended claims.

[0049] The present disclosure provide modules and methods for attenuators suitable for applications including modern communications systems, requiring high linearity, low power consumption, and low temperature dependency. Some embodiments of the modules and methods disclosed herein provide attenuators that preserve signal integrity while controlling the signal power. Some embodiments of the modules and methods disclosed herein have a high dynamic range, low insertion loss, wide attenuation range, and wide frequency bandwidth. Some of the embodiments of the modules and methods disclosed herein are suitable for operation in the mid-band (c-band) for fifth-generation (5G) communications.

[0050] In some embodiments disclosed herein, modules and methods provides radio frequency (RF) attenuation tuning with an analog type tuning approach with digital control. In some embodiments disclosed herein, modules and methods provides a digital attenuator with 512 incremental steps of ±0.05 decibel (dB) and a total attenuation range of 26.52 dB.

[0051] Some embodiments of the modules and methods disclosed herein provide a digital attenuator comprising bridged-T network fixed-attenuator bits and fixed phase-change elements in a crystalline state. In some embodiments disclosed herein, the phase-change elements comprise single-pole, three-throw (SP3T), monolithically integrated to switch fixed crystalline phase-change elements arranged in a cascade and bridged-T networks to provide high precision attenuation tuning.

[0052] In some embodiments disclosed herein, the phase-change elements are devices comprised of chalcogenide phase-change material (PCM) such as germanium telluride (GeTe). The PCM devices such as the GeTe-based PCM devices provide suitable performance for RF and millimeter wave (mmWave) applications. PCM-based switches may be monolithically and/or heterogeneously integrated with various other technologies without any need for packaging, which makes these devices affordable and attractive for implementation as reconfigurable RF components. As a result of GeTe exhibiting non-volatile properties, PCM devices provide latching characteristics that do not require a constant steady-state direct current (DC) power to hold switch states. The use of a non-volatile technology in RF reconfigurable attenuators greatly reduces the consumption of static DC power. Further, such technologies greatly reduce chip and/or die size footprints as single-pole single-throw (SPST) switches and routing paths may be densely packed. Multi-port switches (such as SP3T and single-pole two-throw (SP2T) switches) and bridged-T networks in fixed attenuators may be monolithically integrated in multi-stage tuning configurations. Further, GeTe material in crystalline state may be used to provide intentional loss in signal paths for reducing step sizes between attenuator stages.

[0053] RF PCM-based SPST switches discussed herein provide favourable characteristics as they relate to broadband operation frequency, highly miniaturized chip/die size, low insertion loss, low control voltage requirement, latching operation, improved power handling capability, and reasonable linearity and switching time. Based on suitable RF switch aspects, appropriate compact multi-port RF PCM-based SP2T and SP3T switches may be provided.

[0054] Multi-port switches may have similar junction dimensions as those of the SPST switches developed using microfabrication processes. FIG. **1**A illustrates a layout of a SP2T switch **100** and FIG. **1**B illustrates a layout of a SP3T switch **130** according to some embodiments disclosed herein. Any RF device with more than two RF ports in a coplanar waveguide (CPW) configuration may require interconnection of RF ground connections. In some embodiments disclosed herein, RF grounds can be connected in the microfabrication processes. The distance between metal layers and the dielectric constant therebetween can cause large parasitic capacitances, which may result in impedance mismatches to a RF signal line, which may be around 5052, for example. In some embodiments disclosed herein, the SP2T and SP3T switch cores have similar ground connections and the RF signal path therein are optimized, as further described herein, to maintain characteristic impedances. Optimizing impedance and loss of overlapping metal layers is especially important especially for mmWave devices, as parasitic capacitance may block signal flow if not properly addressed during design. FIG. **2**A illustrates an optical micrograph of a SP2T switch and FIG. **2**B illustrates an optical micrograph of a SP3T switch **130** according to some embodiments disclosed herein.

[0055] Referring to FIG. **1**A and FIG. **2**A, in some embodiments disclosed herein, an RF PCM-based SP2T switch **100** has three ports, namely RFC **102**, RF**1** **104**, and RF**2** **106**. RFC **102** is a common RF input port while RF**1** **104** and RF**2** **106** are two RF output ports. In some embodiments disclosed herein, a SP2T switch **100** comprises two RF PCM-based switches. Referring to FIG. **2**A, CTRL**1** **110**, CTRL**2** **112** and GND **112** are control signals. Providing an actuation pulse (for example, an amorphous pulse or a crystalline pulse) between CTRL**1** **110** and GND **110** actuates the switch between RFC **102** and RF**1** **104** to provide a signal path from input RFC **102** to output RF**1** **104**. Providing an actuation pulse between CTRL**2** **112** and GND **114** actuates the switch between RFC **102** and RF**2** **106** to provide a signal path between RFC **102** and RF**2** **106**. As a result of the compact dimensions of RF PCM-based switches, the switches may be placed as close to a T-junction or T-shaped RF intersections as practicable to minimize any reflected RF signals from the non-connected port.

[0056] In some embodiments disclosed herein, a PCM-based SP3T switch **130** is shown in FIG. **2**B which operates similarly to the RF PCM-based SP2T switch **100**, having RFC **132**, RF**1** **134** and RF**2** **136** with an additional RF**3** **138** output port. In some embodiments disclosed herein, RF PCM-based switches are latching switches, meaning that they are non-volatile switches that they may remain in the connected state for a relatively long time without continuous application of the corresponding control signal until another control signal triggers its disconnection, which allows the sharing of control and bias pads. To minimize the number of control pads used, in some embodiments disclosed herein, a SP3T switch **130** is designed using only four control pads, namely CTRL**1** **140**, CTRL**3** **142**, and two shared pads GND/CTRL**2** **144** and CTRL2/GND **146**. Providing an actuation pulse between CTRL**1** **140** and GND/CTRL**2** **144** (where GND/CTRL**2** **144** acts as a ground terminal) actuates the switch between RFC **132** and RF**1** **134** to provide a signal path from input RFC **132** to output RF**1** **134**. Providing an actuation pulse between GND/CTRL**2** **144** and CTRL**2**/GND **146** actuates the switch between RFC **132** and RF**2** **136** to provide a signal path from input RFC **132** to output RF**2** **136**. Providing an actuation pulse between CTRL**3** **142** and CTRL2/GND **146** (where GND/CTRL**2** **146** acts as a ground terminal) actuates the switch between RFC **132** and RF**3** **138** to provide a signal path from input RFC **132** to output RF**3** **138**. In some embodiments disclosed herein, the PCM-based SP3T switch **130** may comprise one or more dummy pads of switches that are not connected.

[0057] In some embodiments disclosed herein, a RF PCM-based switch junction (or a PCM-based SPST switch core) in SPST switches are about 20 μm×20 μm in size while the overall size of the SPST switch is about 500 μm×400 μm. The additional area of the SPST switch other than the switch junction is for RF ports and bias pads. RF CPW port sizes can be designed to meet a variety of purposes, including to meet the requirements of a ground-signal-ground (GSG) probe pitch size. GSG probes are manufactured with pitch sizes varying from about 50 μm to 250 μm, thus the overall device size may depend largely on the desired probe pitch size. Overall device sizes are determined including all RF ports and bias pads (which depends on GSG probe pitches). If a core is smaller in size than a port size, it not only increases the overall device size, but also introduces additional RF signal transmission loss due to length and tapering of a RF signal path. In embodiments disclosed herein, a RF SPST switch is designed to accommodate GSG probe pitches between about 100 μm to 250 μm.

[0058] FIG. **3** illustrates an optical micrograph of an embodiment of a RF PCM-based SP3T switch **150** with a larger port size. Switch functionality and performance are substantially identical to the SP3T switch **130** illustrated in FIG. **1**B and FIG. **2**B with a different RF port size to accommodate larger probe pitches (for example, about 150 μm). Referring to FIG. **3**, a SP3T core **152** is illustrated with an inset having dimensions about 76 μm×76 μm, which is highly miniaturized and may be monolithically integrated into any RF device. The overall device area of the SP3T switch **130** in FIG. **2**A and the SP3T switch **130** in FIG. **2**B is less than about 300 μm×300 μm, while the overall device size of the SP3T switch **150** in FIG. **3** is about 600 μm×600 μm.

[0059] FIG. **4** illustrates simulated and measured performance of RF parameters of an embodiment of a SP3T switch. Due to similar and symmetrical device core structures, the performance of an embodiment of a SP2T switch is substantially identical to the SP3T switch. Referring to FIG. **4**, the SP3T switch showed lower than 1.2 dB insertion loss and better than 16 dB isolation. Return loss is greater than 18 dB over the frequency range. Measured parameters match closely with electromagnetic field (EM) simulations as all material parameters required for EM simulations were taken by measuring various test structures of the switch. Measurements of the switch had greater than 41 dBm input third-order intercept point (IIP3) and was able to handle at least 3.5 W continuous wave (CW) power (not including self-actuating concerns) and may be improved by modifying the RF PCM-based switch junction dimensions.

[0060] FIG. **6** illustrates four SP3T switches arranged in series with a first pair of SP3T switches defining three paths, t_0, t_1 and t_2, and a second pair of SP3T switches defining three paths, t_0, t_3 and t_4. FIG. **7** illustrates S3PT switches arranged in a similar topology as a pair of SP3T switches where the t_0 path is optimized using the compensated S_0. In some embodiments, this is achieving by adjusting the width and length of GeTe element of the t_0 section.

[0061] In some embodiments disclosed herein, unit **160** comprises a unit input **162** and a unit output. The unit **160** comprises a first, a second, and a third selectable conductive path **164**, **166**, and **168**, where the first path **164** comprises a first attenuation element **165** and the second path **166** comprises a second attenuation element **167**. The third path **168** may be optimized as described above relating to the t_0 path of FIG. **7**. The unit **160** comprises a switching element for selectably connecting the unit input **162** to the unit output via one of the three selectable conductive paths **164**, **166**, and **168**. Referring to FIG. **5**, in an embodiment, the switching element is a SP3T switch **130** connected to the RF input or unit input **162** and three selectable conductive paths **164**, **166**, and **168**, wherein the first path **164** has a first attention element **165** with an attenuation of 3 dB and the second path **166** has a second attenuation element **167** with an attenuation of 6 dB. In some embodiments disclosed herein, the unit **160** further comprises a second switching element for connecting the three selectable conductive paths **164**, **166**, and **168** to the unit output.

[0062] Referring to FIG. **6**, a portion **180** comprises two units **160** connected in series. Referring to FIG. **6**, the unit output **170** of the first unit **160** is connected to the unit input **162** of the second unit **160**. In some embodiments disclosed herein, a module **190** comprises two or more portions **180** connected in series. Referring to FIG. **8**, a module **190** comprises three portions **180** or stages: a first stage (X-Stage) **180**X, a second stage (Y-Stage) **180**Y and a third stage (Z-Stage) **180**Z.

[0063] In some embodiments, the module **180** comprises a third unit wherein the unit output **170** of the second unit **160** is connected to the unit input **162** of the third unit. In some embodiments, the module **180** comprises four or more units **160** following the same configuration pattern.

[0064] In some embodiments, for each unit **160**, the signal attenuation of the first attenuation element **165** is greater than the signal attenuation of the second attenuation element **167**. Further, in some embodiments, for each portion **180**, the signal attenuation of the first attenuation element **165** of the second unit **160** is greater than the signal attenuation of the second attenuation element **167** of the first unit **160**. Alternatively, in some embodiments, for each portion **180**, the signal attenuation of the first attenuation element **165** of the first unit **160** is greater than the signal attenuation of the second attenuation element **167** of the second unit **160**.

[0065] In some embodiments, the signal attenuation of the first attenuation element **165** of the first unit **160** of the second portion **180** is greater than the signal attenuation of the second attenuation element **167** of the second unit **180** of the first portion **180**. In some embodiments, the order of the first portion **180** and second portion **180** is not important. Specifically, in some alternative embodiments, the signal attenuation of the first attenuation element **165** of the first unit **160** of the first portion **180** is greater than the signal attenuation of the second attenuation element **167** of the second unit of the second portion **180**.

[0066] In some embodiments, the module **190** comprises a third portion **180** connected in series. In some embodiments, the signal attenuation of the attenuation elements **165** and **167** of the third portion **180** may be higher or lower than the signal attenuation of the attenuation elements **165** and **167** of the first and second portions **180**.

[0067] While the relative ordering of the portions **180** is not important, a module **190** having portions **180** with attenuation elements **165** and **167** having different signal attenuation provides a system with a broad range and fine tuning. Specifically, portions **180** with attenuation elements **165** and **167** with greater signal attenuation provides a broader range of signal attenuation while portions **180** with attenuation elements **165** and **167** with smaller signal attenuation provides finer tuning of signal attenuation provided by the module **190**.

[0068] In some embodiments disclosed herein, implementations of a three-stage tuning approach including a coarse stage, a fine stage, and an extra fine stage are provided to improve the attenuation precision steps. Referring to FIG. **8**, in an embodiment, a first portion (X-Stage) **180**X comprises attenuation elements providing the lowest signal attenuation, a second portion (Y-Stage) **180**Y comprises attenuation elements providing intermediate signal attenuation, and a third portion (Z-Stage) **180**Z comprises attenuation elements providing the highest signal attenuation elements. In some embodiments, the module **190** comprises any combination of two or more of the first portion **180**X, second portion **180**Y and third portion **180**Z. In an embodiment, the first attenuation element **165** of the first unit **160** of the first portion **180**X is 0.05 dB (A of X-Stage), the second attenuation element **167** of the first unit **160** of the first portion **180**X is 0.1 dB (B of X-Stage), the first attenuation element **165** of the second unit **160** of the first portion **180**X is 0.15 dB (C of X-Stage), the second attenuation element **167** of the second unit **160** of the first portion **180**X is 0.3 dB (D of X-Stage), the first attenuation element **165** of the first unit **160** of the second portion **180**Y is 0.4 dB (A of Y-Stage), the second attenuation element **167** of the first unit **160** of the second portion **180Y** is 0.8 dB (B of Y-Stage), the first attenuation element **165** of the second unit **160** of the second portion **180Y** is 1.2 dB (C of Y-Stage), the second attenuation element **167** of the second unit **160** of the second portion **180Y** is 2.4 dB (D of Y-Stage), the first attenuation element **165** of the first unit **160** of the third portion **180Z** is 3 dB (A of Z-Stage), the second attenuation element **167** of the first unit **160** of the third portion **180**Z is 6 dB (B of Z-Stage), the first attenuation element **165** of the second unit

160 of the third portion 180Z is 9 dB (C of Z-Stage), and the second attenuation element 165 of the second unit 160 of the third portion 180Z is 18 dB (D of Z-Stage). This embodiment provides 26.52 dB of signal attenuation with ±0.05 dB precision in 512 steps. In this embodiment, 12 phase-change SP3T switches are arranged back-to-back in a cascaded chain forming three portions 180 or stages. In some embodiments, the attenuation elements 165 and 167 are fixed phase-change thin-film crystalline elements with increasing resistance to achieve certain attenuation level. Cascading the portions or stages in such an arrangement analog style tuning from a digitally reconfigurable device. FIG. 9 illustrates the various signal attenuation levels or states for each portion 180 or stage, wherein the signal attenuation level of the portions 180 are added together as the portions 180 are connected in series, as follows:

Portion or Stage	State	Bit	Attenuation
X	0	—	0.00
X	1	A	0.05
X	2	B	0.10
X	3	C	0.15
X	4	AC	0.20
X	5	BC	0.25
X	6	D	0.30
X	7	AD	0.35
X	8	BD	0.40
Y	0	—	0.0
Y	1	A	0.4
Y	2	B	0.8
Y	3	C	1.2
Y	4	AC	1.6
Y	5	BC	2.0
Y	6	D	2.4
Y	7	AD	2.8
Y	8	BD	3.2
Z	0	—	0
Z	1	A	3
Z	2	B	6
Z	3	C	9
Z	4	AC	12
Z	5	BC	15
Z	6	D	18
Z	7	AD	21
Z	8	BD	24

[0069] In some embodiments, the module 190 comprises one or more amplifiers located between the units 160 and/or the portions 180. In some embodiments, the module 190 comprises one or more matching networks located between the units 160 and/or the portions.

[0070] FIG. 10A to FIG. 10F illustrate attenuation responses of the first portion or stage (X-Stage) 180X, the second portion or stage (Y-Stage) 180Y, and the third portion or stage (Z-Stage) 180Z. More specifically, FIG. 10A illustrates the attenuation levels of the first stage 180X, FIG. 10B illustrates the return losses of the first stage 180X, FIG. 10C illustrates the attenuation levels of the second stage 180Y, FIG. 10D illustrates the return losses of the second stage 180Y, FIG. 10E illustrates the attenuation levels of the third stage 180Z, and FIG. 10F illustrates the return losses of the third stage 180Z.

[0071] FIG. 11 illustrates the attenuation levels of the first stage 180X, the second stage 180Y, and the third stage 180Z, including illustrating that the range of the first stage 180X is within one of the increments of the second stage 180Y and the range of the second stage 180Y is within one of the increments of the third stage 180Z. FIG. 12 illustrates the minimum and maximum signal attenuation ranges.

[0072] FIG. 13 illustrates the physical layout of a phase-change element and a cross-section thereof including composite layers comprising high resistivity silicon wafer (HRSi), silicon oxide (SiO_2), germanium telluride (GeTe), titanium and gold (Ti+Au), silicon nitride (SiNx), silver (Ag), chromium and gold (Cr+Au), alumina nitride (AlN), and tungsten (W). FIG. 14 is an illustration of an attenuator chip layout showing signal paths, control pads, and junctions. FIG. 15 is an illustration of an optical micrograph of a fabricated chip showing bridged-T resistor networks.

[0073] FIG. 16 is a flowchart showing the steps of a method 1600, according to one embodiment of the present disclosure. The method 1600 begins with setting signal attenuation of a first unit, (step 1602). At step 1604, signal attenuation of a second unit is set. At step 1606, signal attenuation of a third unit is set. At step 1608, signal attenuation of a fourth unit is set. Optionally, at step 1610, signal attenuation of a fifth unit is set. Optionally, at step 1612, signal attenuation of a sixth unit is set.

1. A module comprising two portions, each portion comprising a first unit and a second unit, each of the units comprising:
   - a unit input;
   - a unit output;
   - a first, a second, and a third selectable conductive path, the first path comprising a first attenuation element and the second path comprising a second attenuation element; and
   - an input switching element for selectably connecting the unit input to the unit output via one of the three selectable conductive paths;
   - wherein the unit output of the first unit of each portion is connected to the unit input of the second unit thereof; and
   - wherein the unit output of the second unit of the first portion is connected to the unit input of the first unit of the second portion.

2. The module of claim 1, wherein for each unit, signal attenuation of the second attenuation element is greater than signal attenuation of the first attenuation element.

3. The module of claim 1, wherein for each portion, signal attenuation of the first attenuation element of the second unit is greater than signal attenuation of the second attenuation element of the first unit.

4. The module of claim 1, wherein signal attenuation of the first attenuation element of the first unit of the second portion is greater than signal attenuation of the second attenuation element of the second unit of the first portion.

5. The module of claim 1, wherein for each unit of a third portion of the module, signal attenuation of the second attenuation element is greater than signal attenuation of the first attenuation element.

6. The module of claim 1, wherein for a third portion of the module, signal attenuation of the first attenuation element of the second unit is greater than signal attenuation of the second attenuation element of the first unit.

7. The module of claim 1, wherein signal attenuation of the first attenuation element of the first unit of a third portion of the module is greater than signal attenuation of the second attenuation element of the second unit of the second portion.

8. The module of claim **1**, comprising one or more additional portions, each additional portion comprising a first unit and a second unit, each of the units comprising:

a unit input;

a unit output;

a first, a second, and a third selectable conductive path, the first path comprising a first attenuation element and the second path comprising a second attenuation element; and

an input switching element for selectably connecting the unit input to the unit output via one of the three selectable conductive paths;

wherein the unit output of the first unit is connected to the unit input of the second unit.

9. The module of claim **1**, wherein each of the input switching elements is a single pole three-throw switch.

10. The module of claim **1**, wherein each of the input switching elements comprises one or more of: a phase-change material and four control pads and two shared pads for control and biasing.

11. The module of claim **10**, wherein the phase-change material comprises germanium telluride.

12. The module of claim **1**, wherein each of the units further comprises an output switching element connected to the three selectable conductive paths and the unit output for selectably connecting one of the three selectable conductive paths and the unit output.

13. The module of claim **12**, wherein each of the output switching elements is a single pole three-throw switch.

14. The module of claim **12**, wherein each of the output switching elements comprises one or more of: a phase-change material and four control pads and two shared pads for control and biasing.

15. The module of claim **14**, wherein the phase-change material comprises germanium telluride.

16. The module of claim **1**, wherein each of the first attenuation elements and each of the second attenuation elements comprise bridged-T networks.

17. The module of claim **1**, further comprising one or more of: one or more amplifiers between each of the portions and one or more matching networks between each of the portions.

18. A method comprising the steps of:

setting signal attenuation of a first unit;

setting signal attenuation of a second unit;

setting signal attenuation of a third unit; and

setting signal attenuation of a fourth unit,

wherein the first unit, the second, the third unit and the fourth unit are connected in series, and

wherein selecting signal attenuation of a unit comprises selecting one of no attenuation, a first signal attenuation and a second signal attenuation thereof.

19. The method of claim **18**, wherein for each unit, the second signal attenuation is greater than the first signal attenuation.

20. The method of claim **18**, further comprising the steps of:

setting signal attenuation of a fifth unit;

setting signal attenuation of a sixth unit;

wherein the fifth unit and the sixth unit are connected in series with the fourth unit, and

wherein selecting signal attenuation of a unit comprises selecting one of no attenuation, a first signal attenuation and a second signal attenuation thereof.

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