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(54) **COMPLEX DIELECTRIC CONSTANT SENSING SYSTEM AND METHOD**

(71) Applicant: **Taibah University**, Medina (SA)

(72) Inventors: **Muhammad Amin**, Madinah (SA); **Hattan F. Abutarboush**, Madinah (SA); **Rashad Ramzan**, Islamabad (PK); **Omar F. Siddiqui**, Madinah (SA); **Aqsa Ehsan**, Islamabad (PK)

(73) Assignee: **Taibah University**, Medina (SA)

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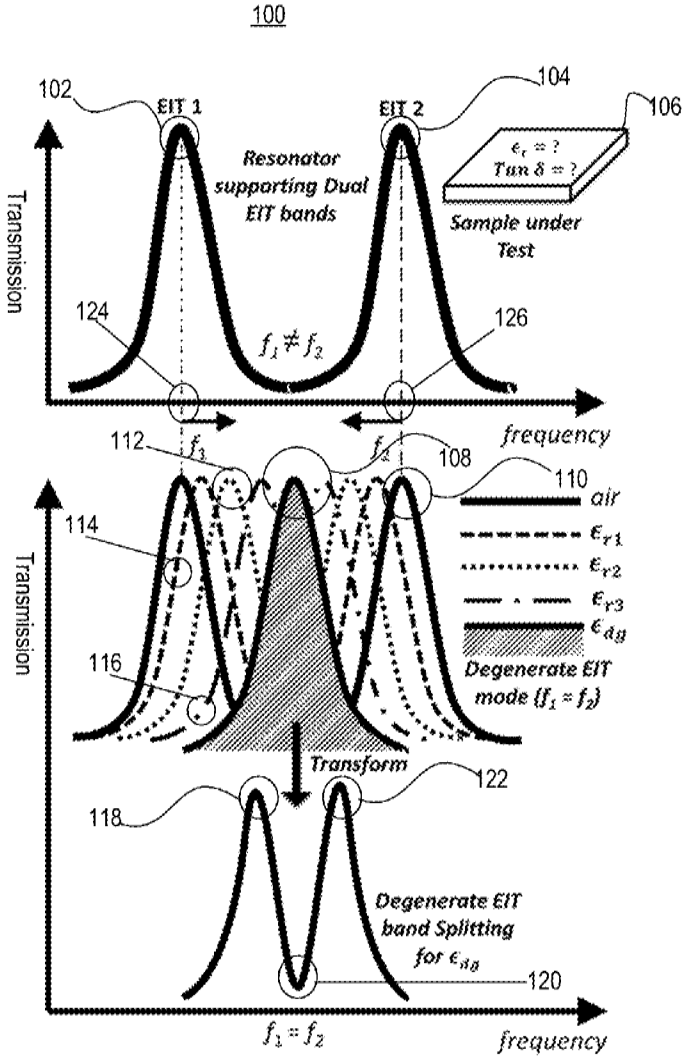
(57) **ABSTRACT**

Described herein is Complex Dielectric Constant Sensor (CDCS) incorporating microstrip based radial stub and open circuit stub pair structures that utilize interference coupling between degenerate EIT modes to detect CDC of sample-under-test (SUT). In at least one embodiment, CDCS generates two distinct EIT modes when sensor is unloaded. In at least one embodiment, coupling between resonator modes and interaction of electromagnetic fields with material is affected indicating presence of dielectric sample. In at least one embodiment, two EIT modes become degenerate, causing cancellation and suppressing transparency window when dielectric constant of SUT matches a specific value. In at least one embodiment, CDCS can detect slight changes in complex dielectric properties of SUT. In at least one embodiment, CDCS can characterize materials such as substrate samples based on their CDCs for design and characterization of microwave devices, antennas, and thin film devices.



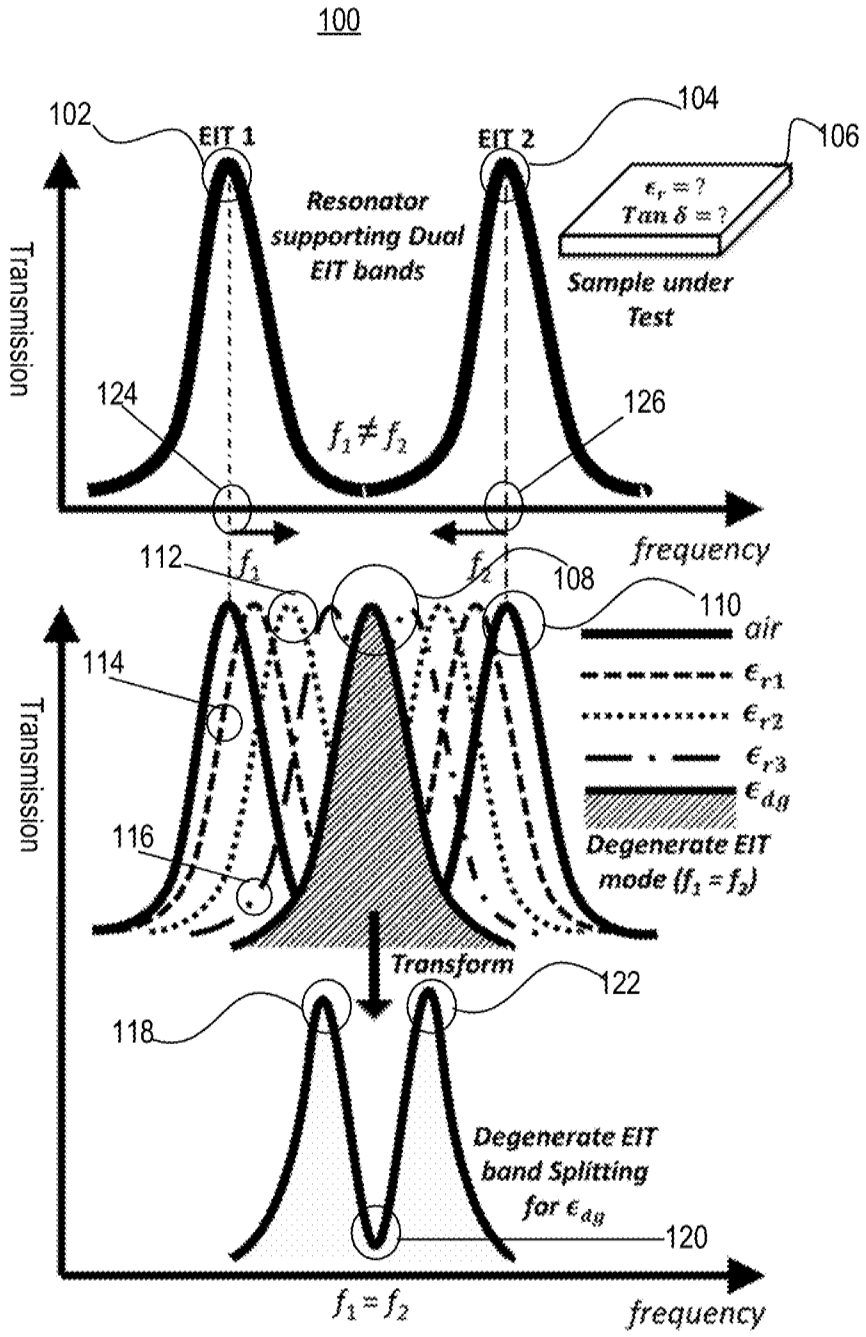

100
102
EIT 1
EIT 2
104
106
Resonator supporting Dual EIT bands
$\epsilon_r = ?$
$Tan\,\delta = ?$
Sample under Test
Transmission
124
126
$f_1 \neq f_2$
frequency
112
f_1
f_2
108
110
air
ϵ_{r1}
ϵ_{r2}
ϵ_{r3}
ϵ_{dg}
114
116
Degenerate EIT mode ($f_1 = f_2$)
Transform
122
118
Degenerate EIT band Splitting for ϵ_{dg}
120
$f_1 = f_2$
frequency

FIG. 1A

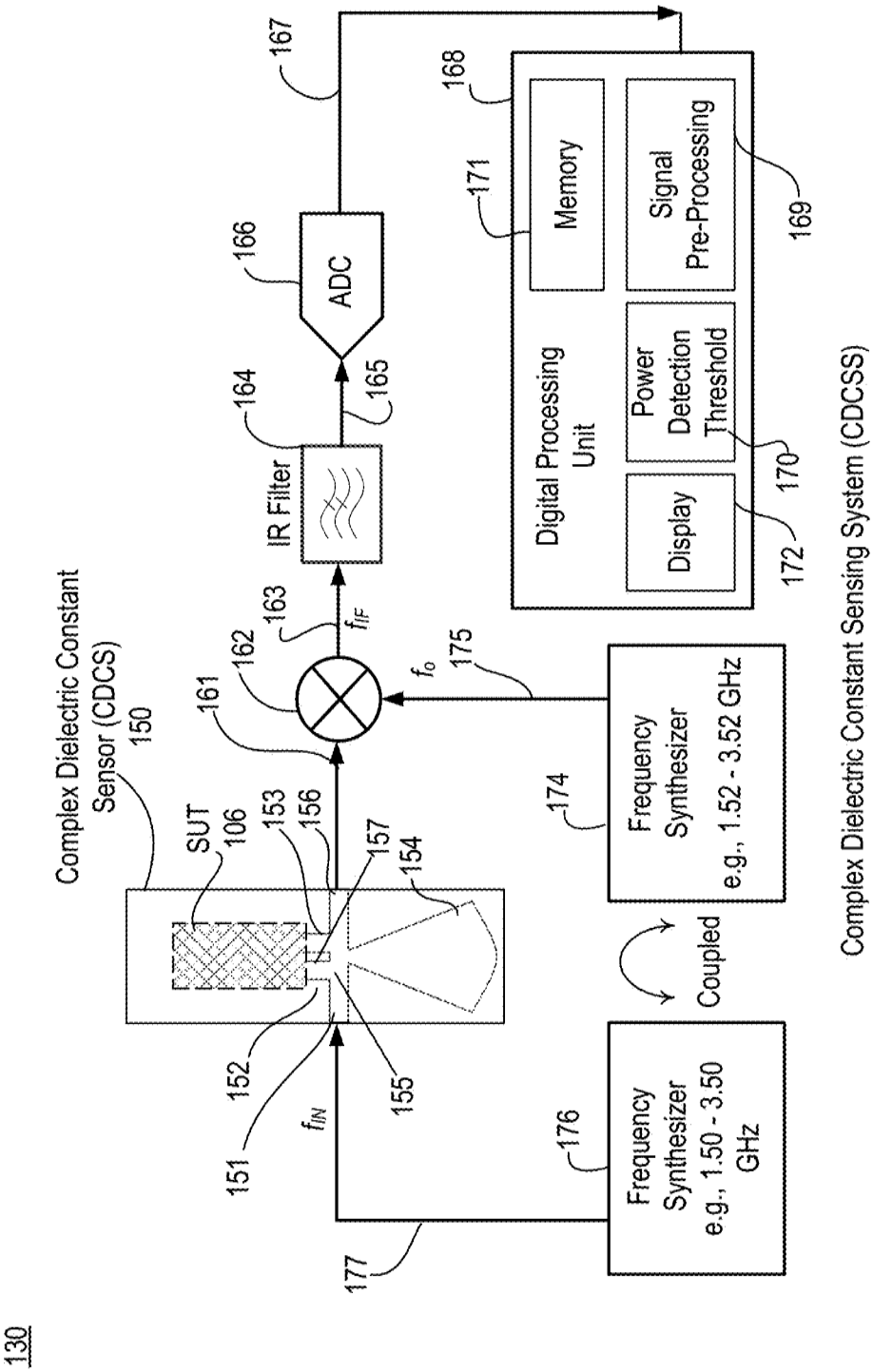

130
Complex Dielectric Constant Sensor (CDCS)
150
SUT
106
151
152
153
154
155
156
157
f_{IN}
161
162
163
f_{IF}
IR Filter
164
165
ADC
166
167
168
Digital Processing Unit
171
Memory
Signal Pre-Processing
169
Power Detection Threshold
170
Display
172
f_o
175
Frequency Synthesizer e.g., 1.52 - 3.52 GHz
174
Coupled
Frequency Synthesizer e.g., 1.50 - 3.50 GHz
176
177
Complex Dielectric Constant Sensing System (CDCSS)

FIG. 1B

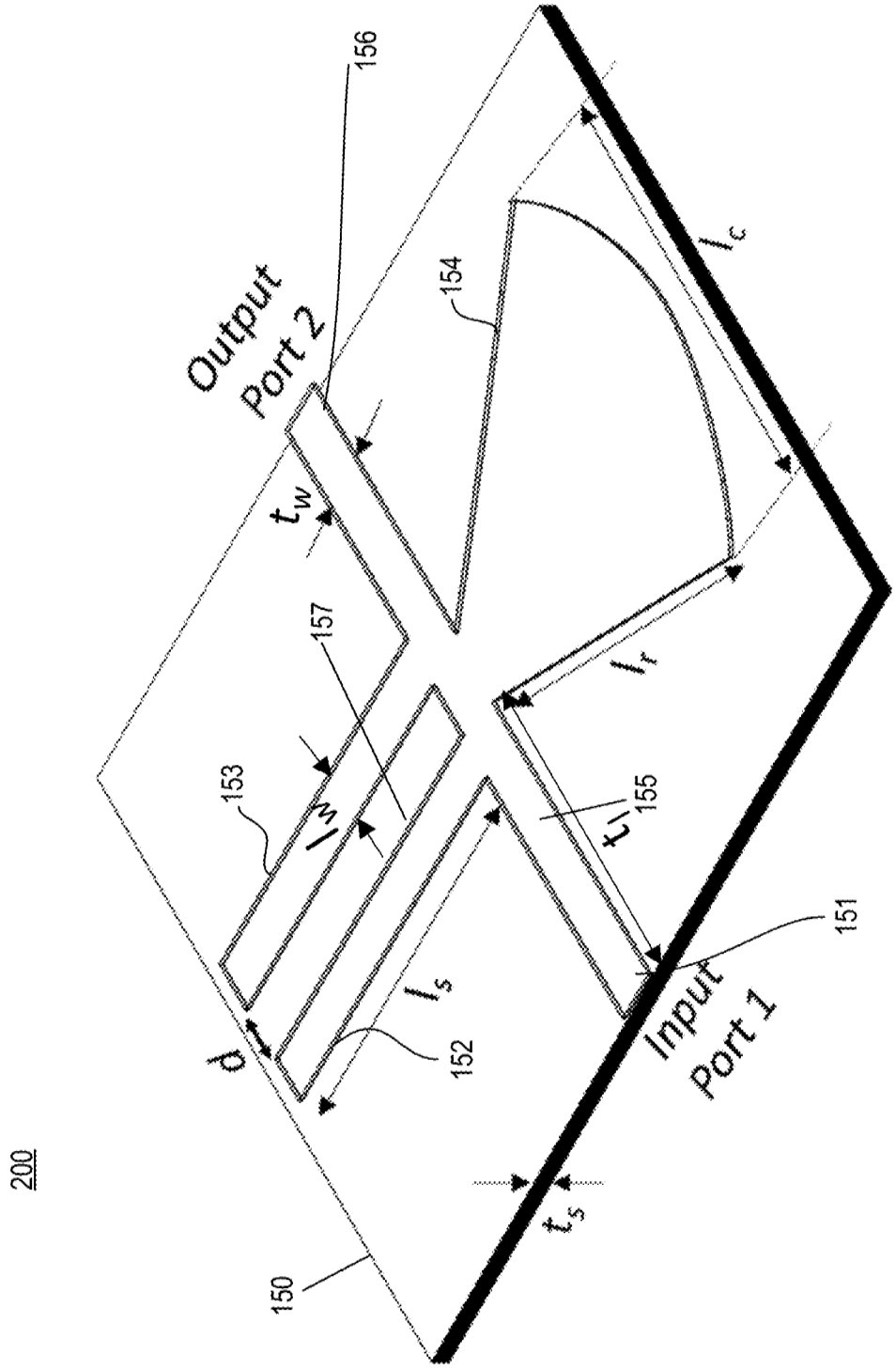

200
150
151
152
153
154
155
156
157
Output Port 2
Input Port 1
t_w
l_w
l_s
l_c
l_f
l_l
t_s
d

FIG. 2A

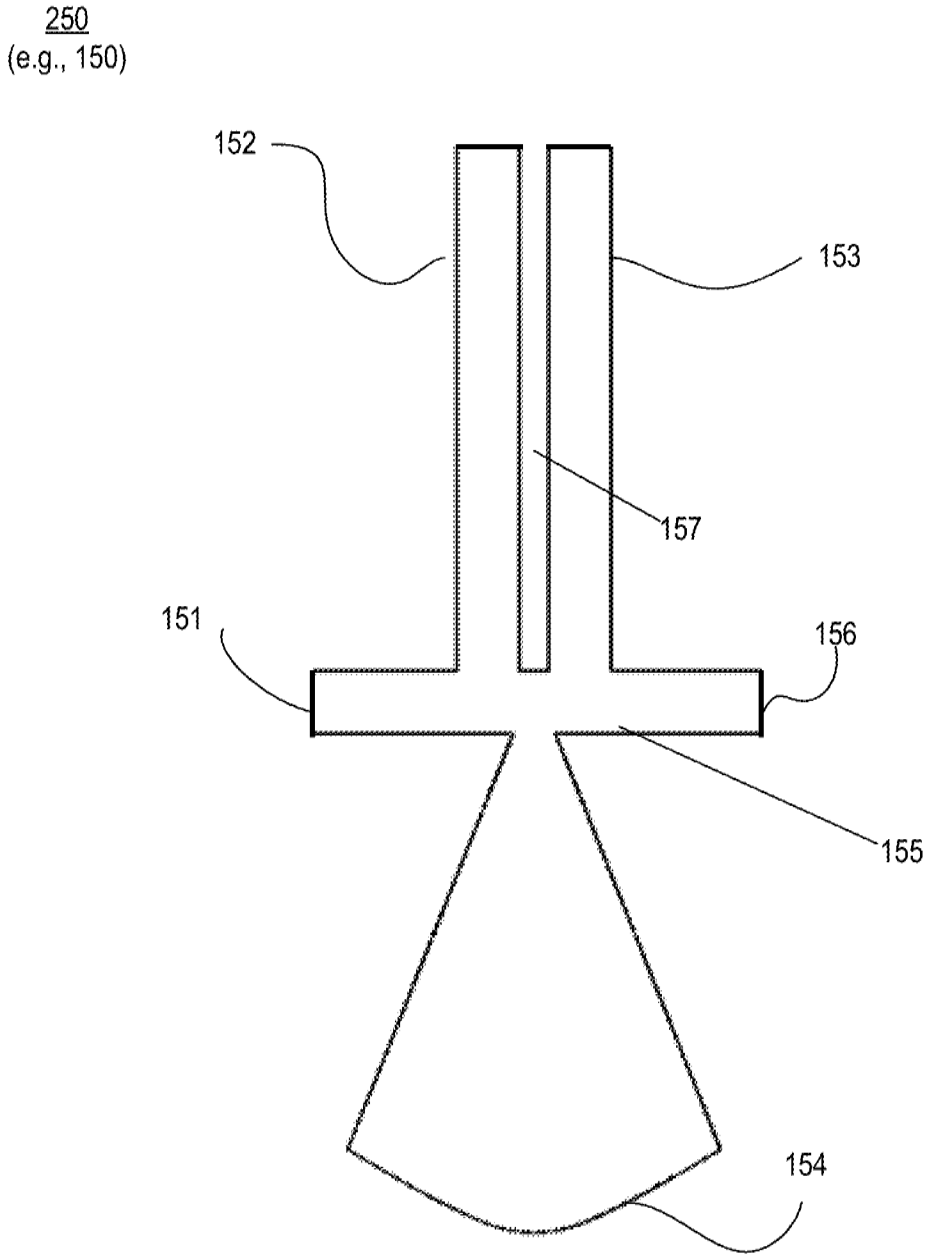


FIG. 2B

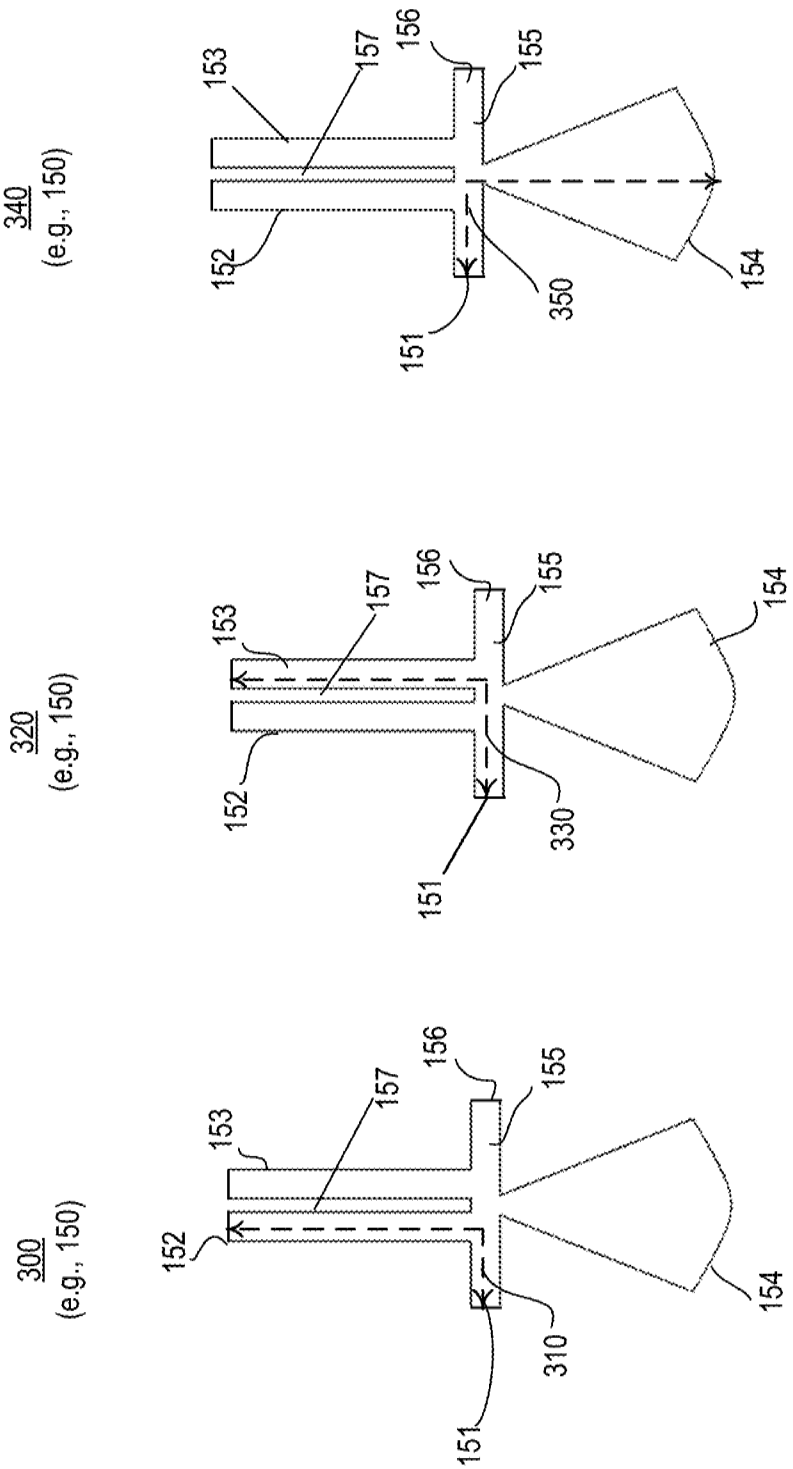

340
(e.g., 150)
153
157
156
155
152
350
151
154
320
(e.g., 150)
153
157
156
155
154
152
330
151
300
(e.g., 150)
153
157
156
155
152
310
151
154

FIG. 3

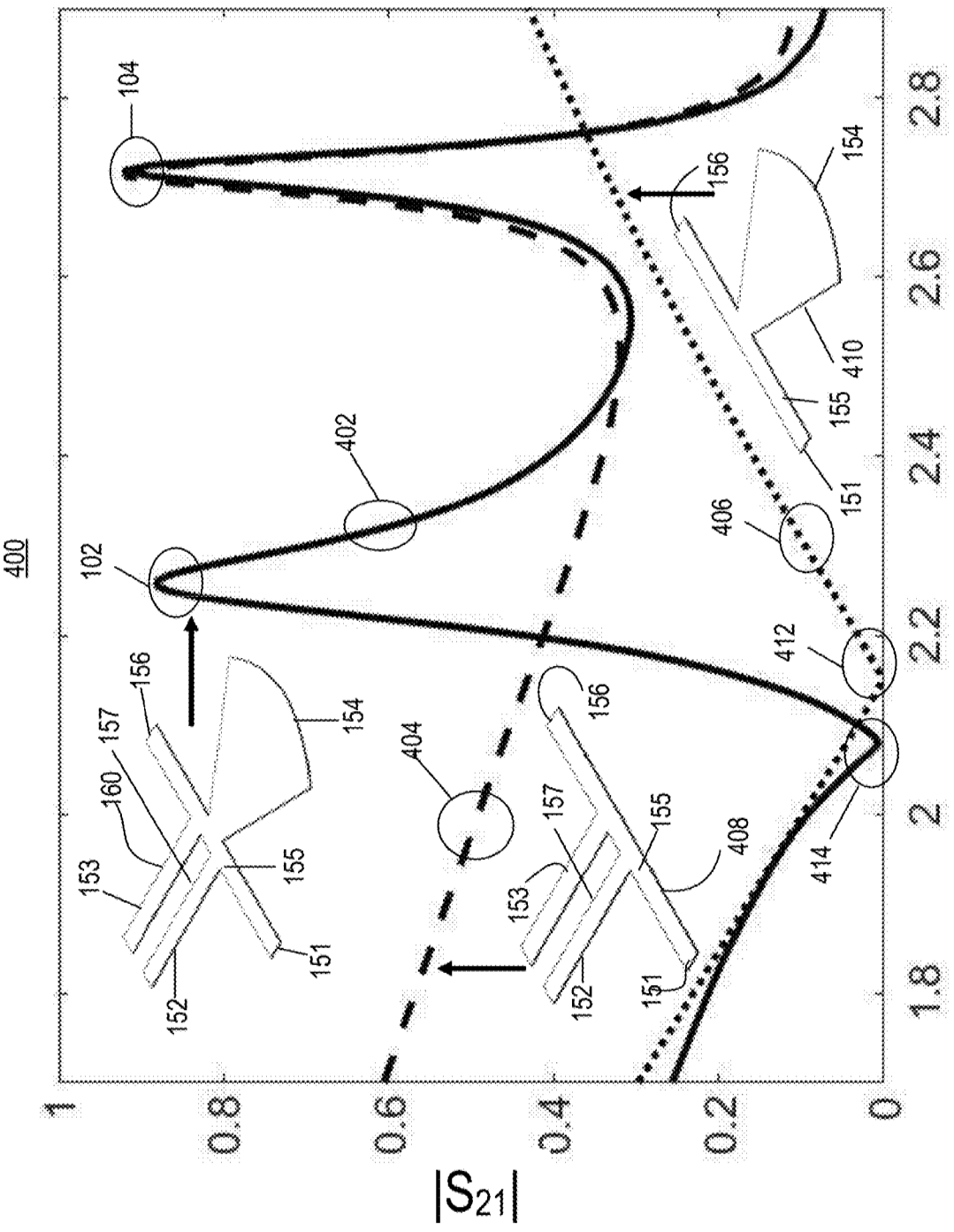

400
|S21|
Frequency (GHz)
0
0.2
0.4
0.6
0.8
1
1.8
2
2.2
2.4
2.6
2.8
102
104
151
152
153
154
155
156
157
160
402
404
406
408
410
412
414

FIG. 4A

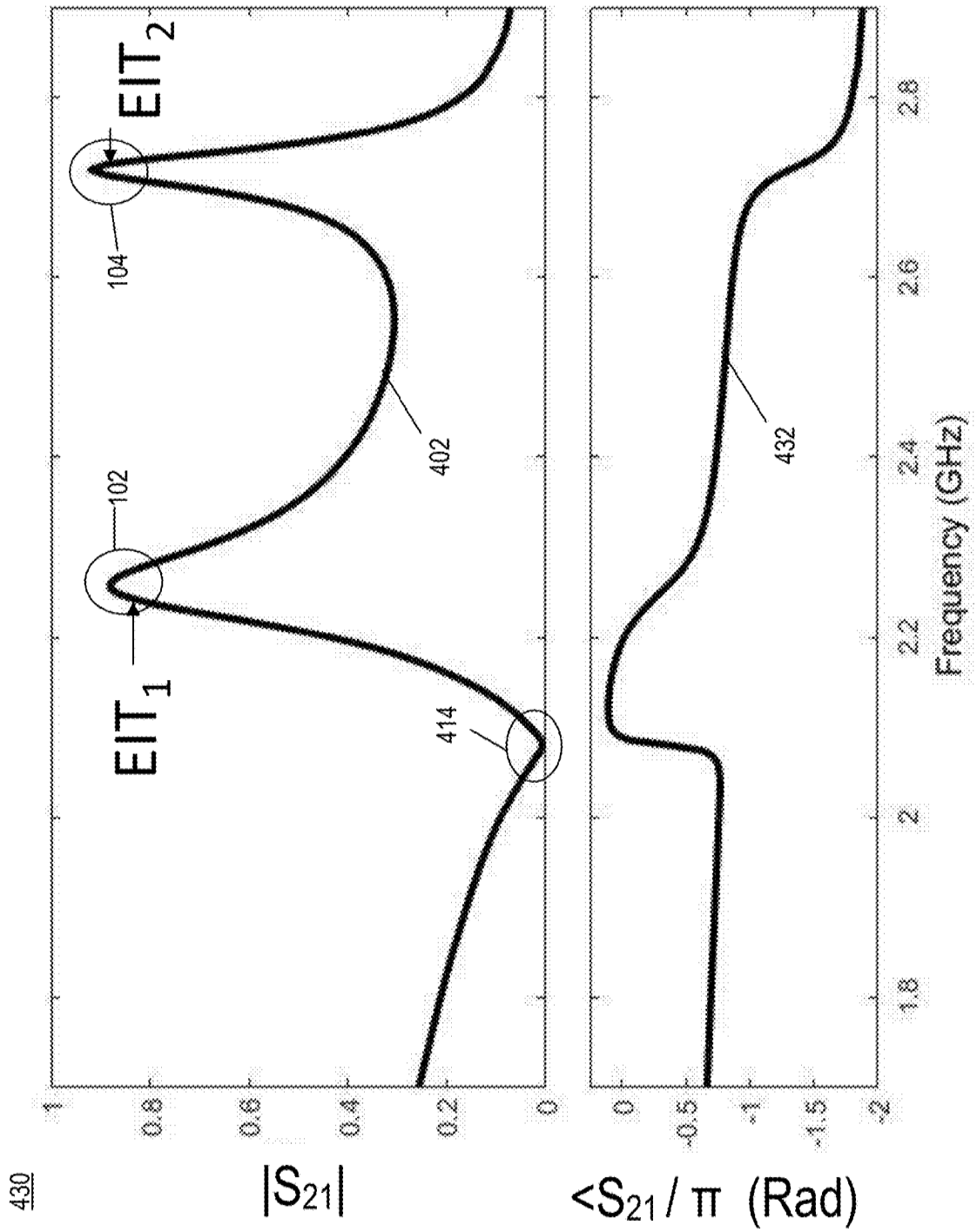

430
EIT1
EIT2
102
104
402
414
432
|S21|
<S21 / π (Rad)
Frequency (GHz)
1
0.8
0.6
0.4
0.2
0
0
-0.5
-1
-1.5
-2
1.8
2
2.2
2.4
2.6
2.8

FIG. 4B

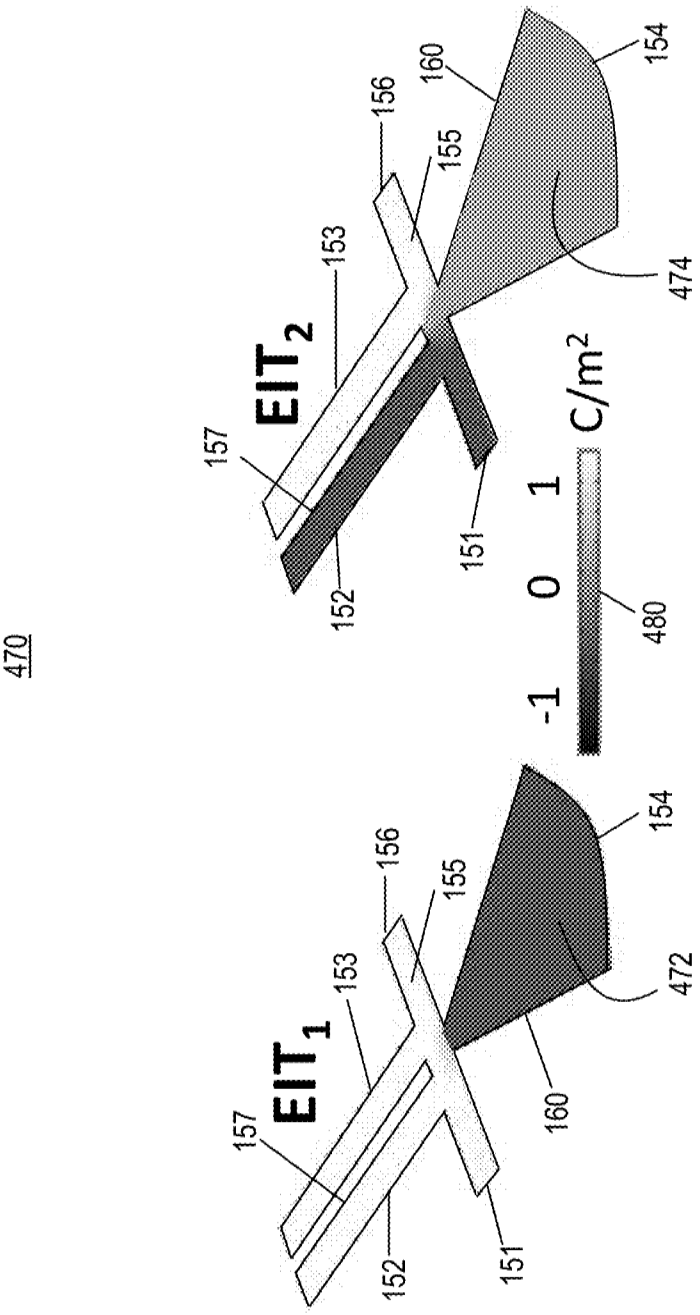

470
EIT2
EIT1
151
152
153
154
155
156
157
160
472
474
480
-1
0
1
C/m2

FIG. 4C

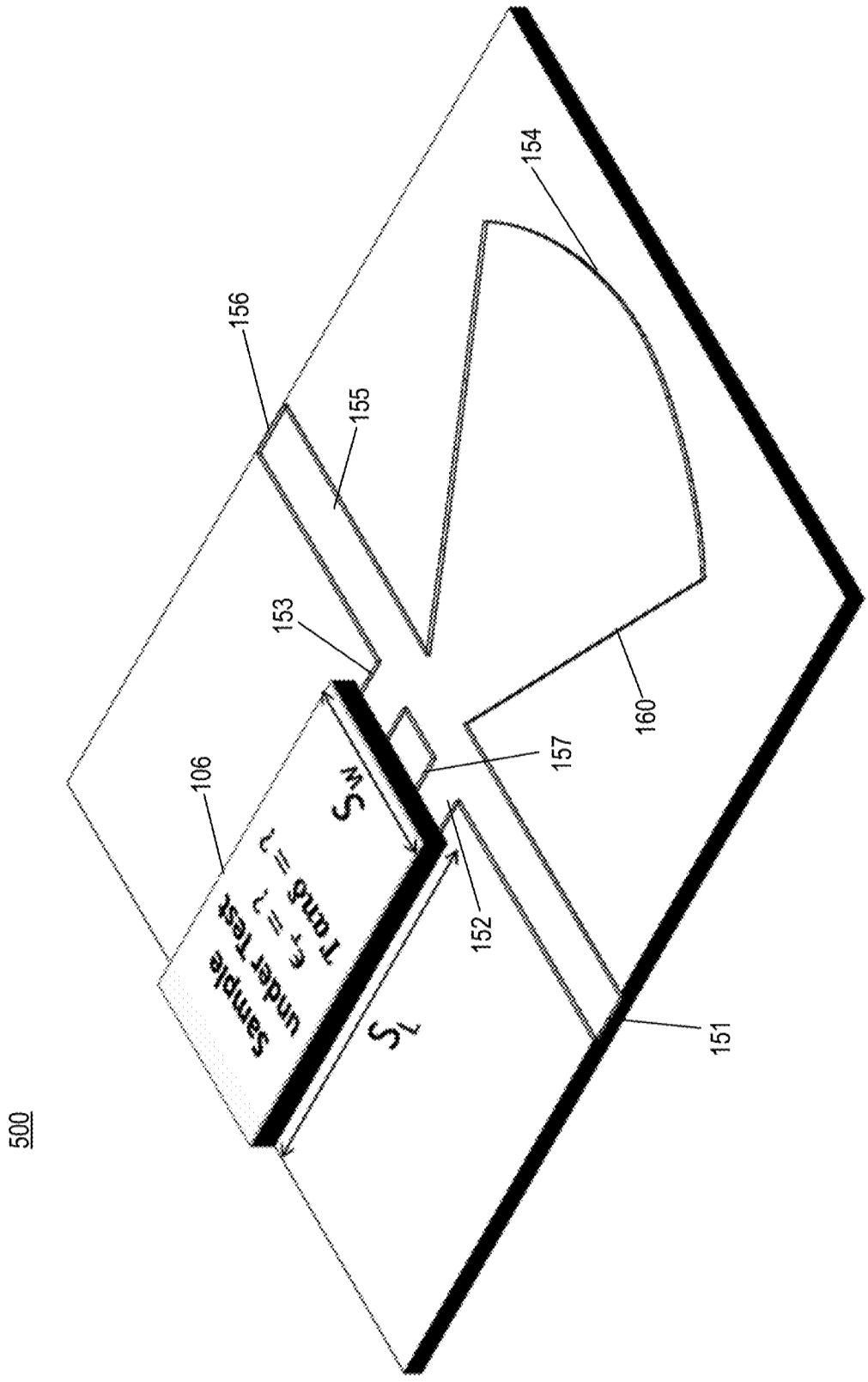

500
106
sample under Test
$\varepsilon_r = ?$
Tand = ?
S_1
S_M
151
152
153
154
155
156
157
160

FIG. 5A

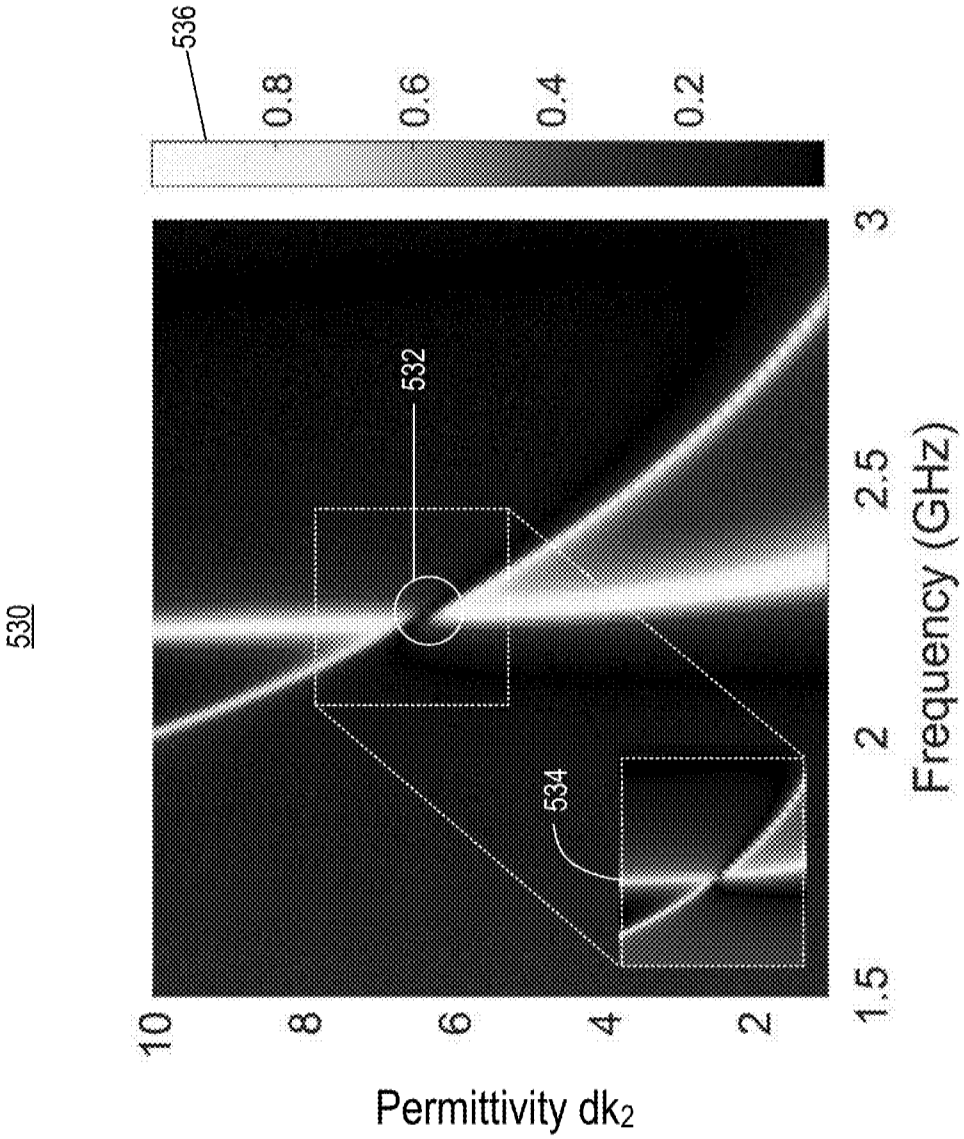

530
536
0.8
0.6
0.4
0.2
532
534
10
8
6
4
2
Permittivity dk2
1.5
2
2.5
3
Frequency (GHz)

FIG. 5B

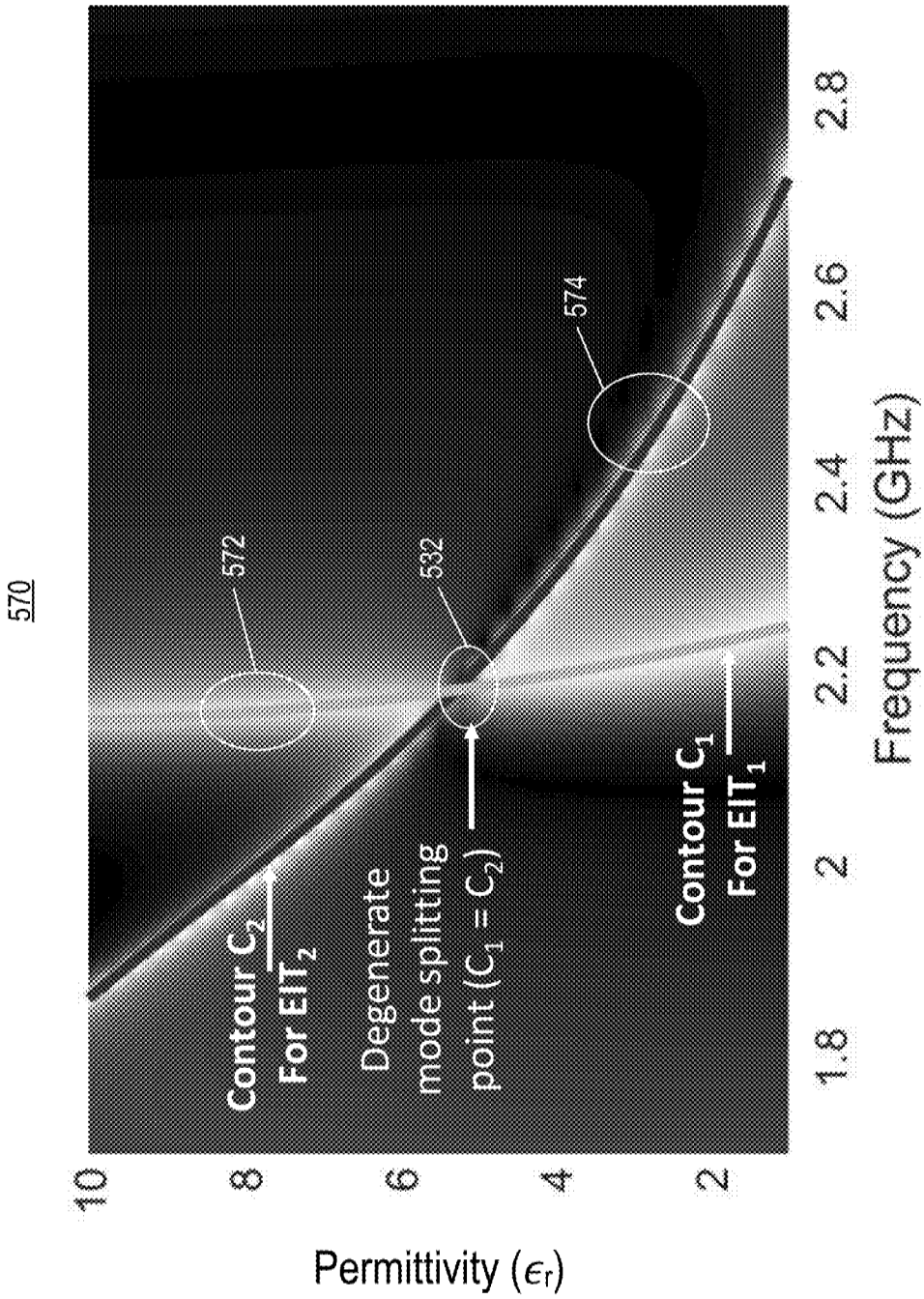

570
572
532
574
Contour C_2 For EIT_2
Degenerate mode splitting point ($C_1 = C_2$)
Contour C_1 For EIT_1
Permittivity (ϵ_r)
10
8
6
4
2
1.8
2
2.2
2.4
2.6
2.8
Frequency (GHz)

FIG. 5C

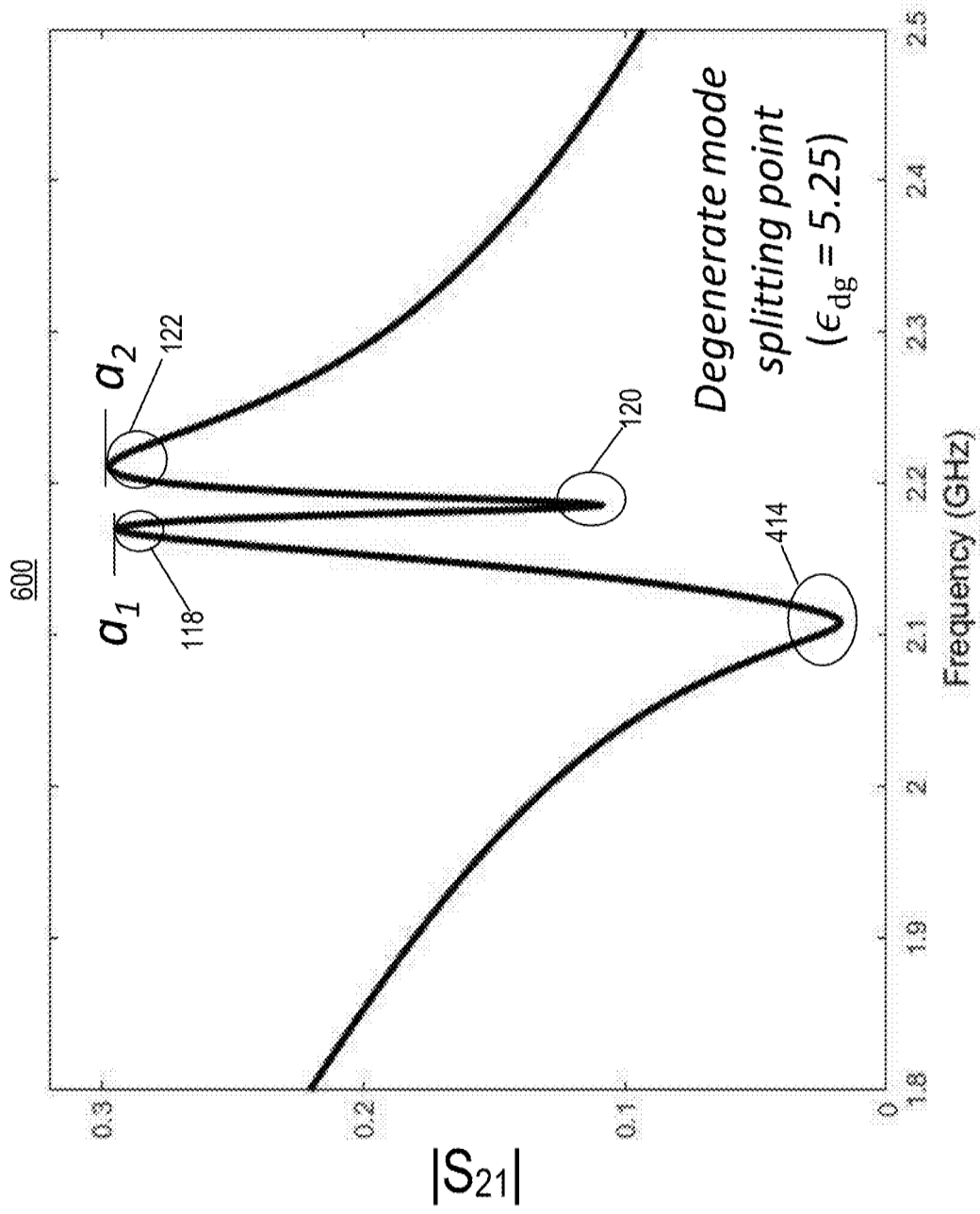

600
a_1
a_2
118
122
120
414
Degenerate mode splitting point ($\epsilon_{dg} = 5.25$)
$|S_{21}|$
Frequency (GHz)
0
0.1
0.2
0.3
1.8
1.9
2
2.1
2.2
2.3
2.4
2.5

FIG. 6A

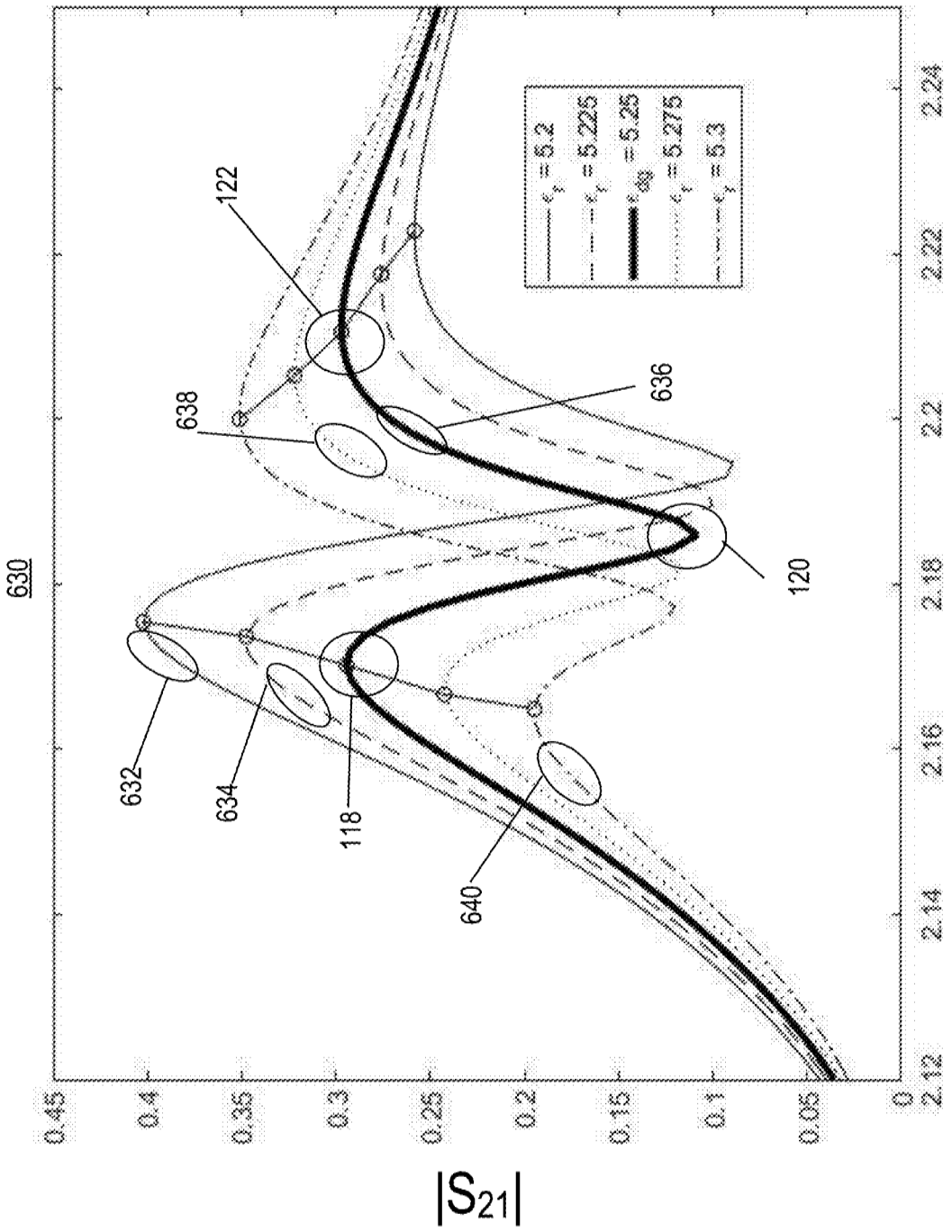

630
122
638
636
120
632
634
118
640
ε_r = 5.2
ε_r = 5.225
ε_{reg} = 5.25
ε_r = 5.275
ε_r = 5.3
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
2.12
2.14
2.16
2.18
2.2
2.22
2.24
Frequency (GHz)
$|S_{21}|$

FIG. 6B

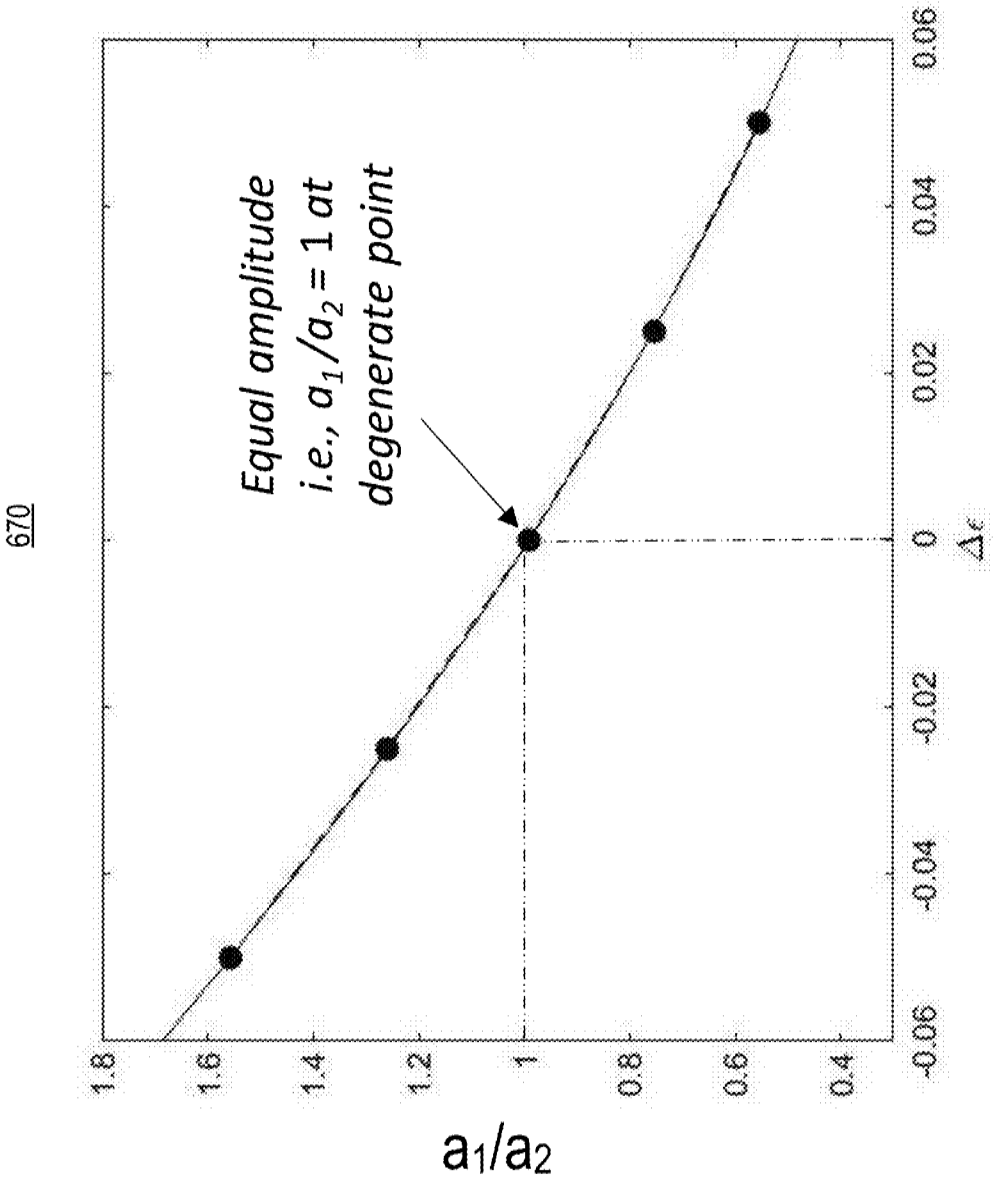

670
Equal amplitude
i.e., $a_1/a_2 = 1$ at
degenerate point
a_1/a_2
$\Delta\epsilon$
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.06
0.04
0.02
0
-0.02
-0.04
-0.06

FIG. 6C

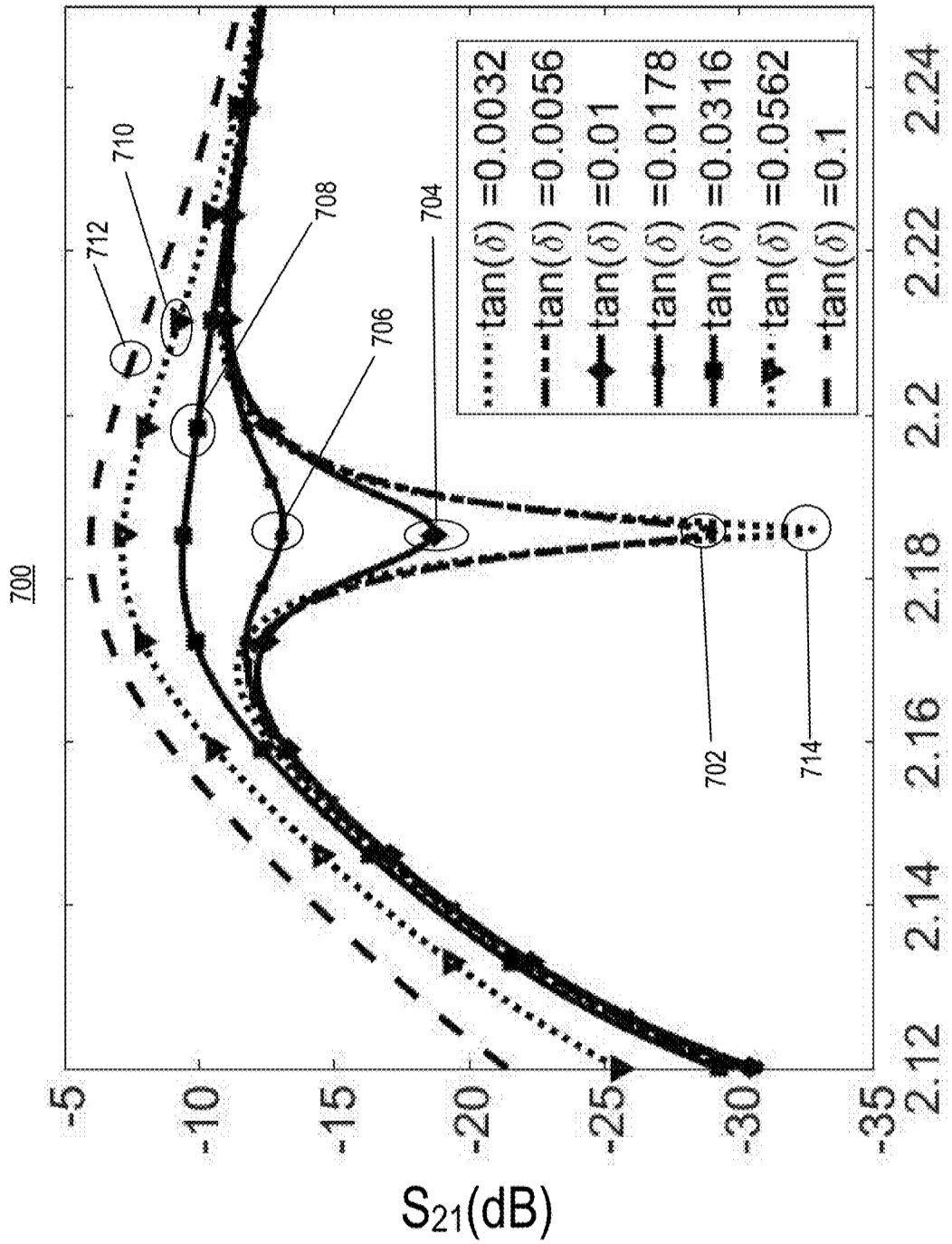

700
702
704
706
708
710
712
714
tan(δ) =0.0032
tan(δ) =0.0056
tan(δ) =0.01
tan(δ) =0.0178
tan(δ) =0.0316
tan(δ) =0.0562
tan(δ) =0.1
-5
-10
-15
-20
-25
-30
-35
2.12
2.14
2.16
2.18
2.2
2.22
2.24
S21(dB)
Frequency (GHz)

FIG. 7A

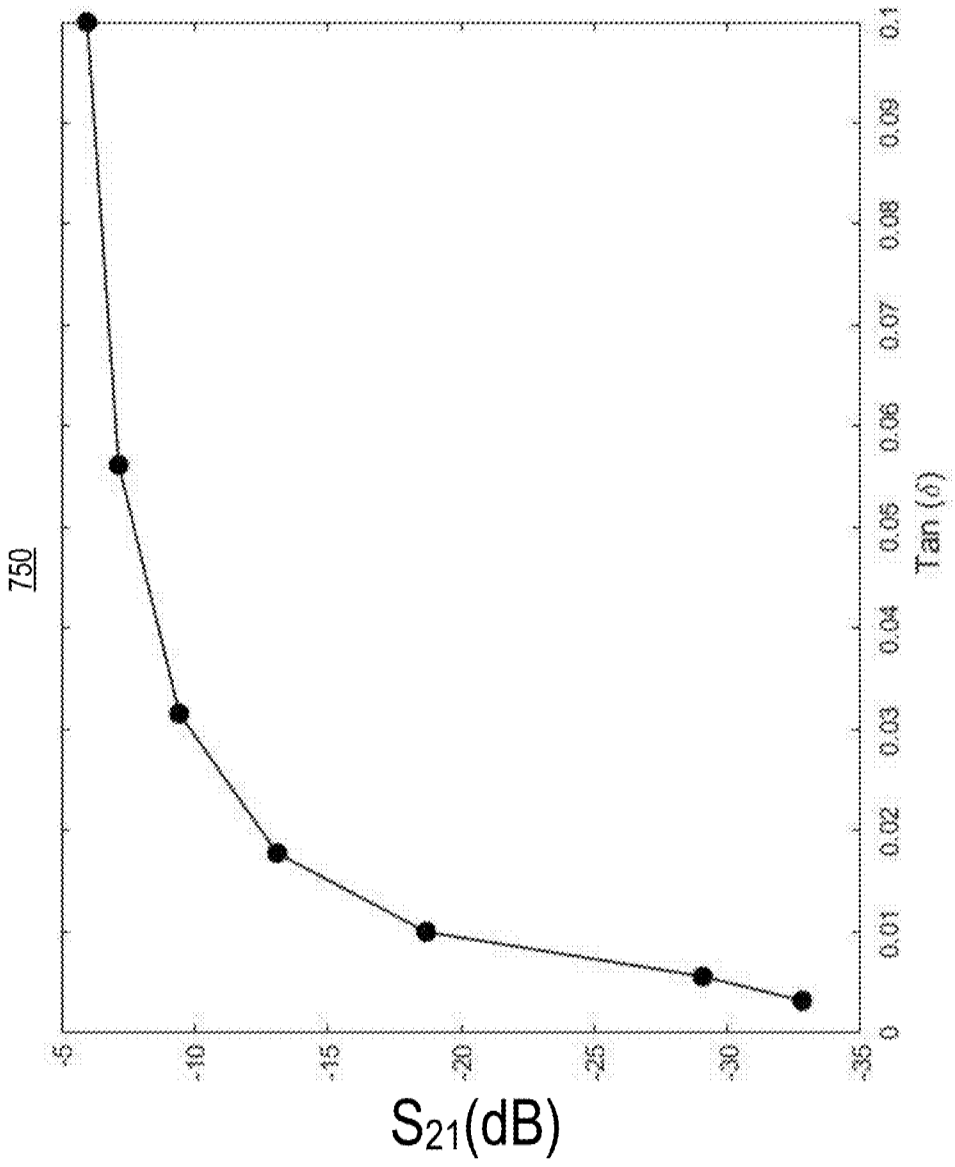

750
-5
-10
-15
-20
-25
-30
-35
S_{21}(dB)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Tan (δ)

FIG. 7B

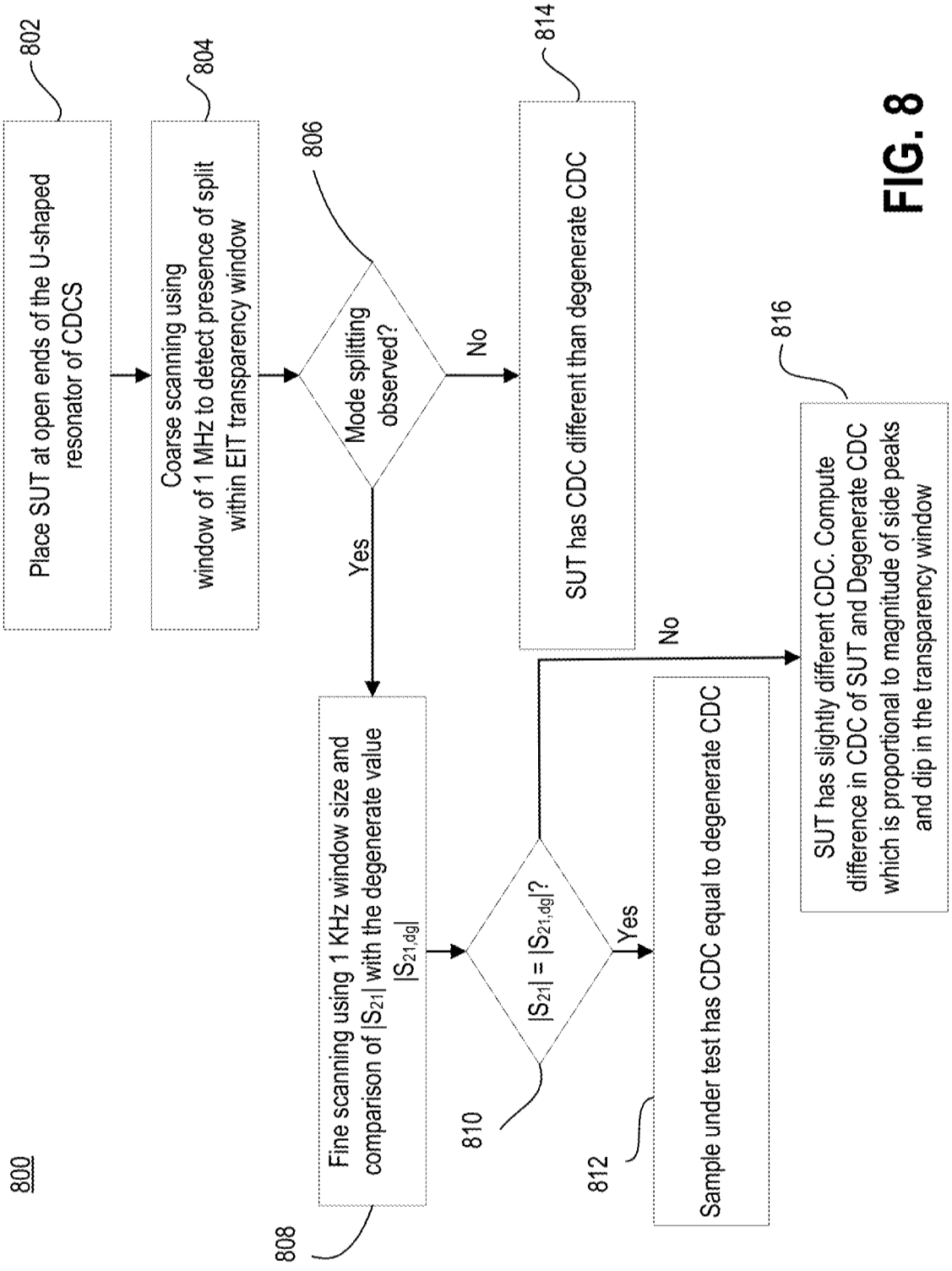

800
802
Place SUT at open ends of the U-shaped resonator of CDCS
804
Coarse scanning using window of 1 MHz to detect presence of split within EIT transparency window
806
Mode splitting observed?
No
814
SUT has CDC different than degenerate CDC
Yes
808
Fine scanning using 1 KHz window size and comparison of |S21| with the degenerate value |S21,dg|
810
|S21| = |S21,dg|?
No
816
SUT has slightly different CDC. Compute difference in CDC of SUT and Degenerate CDC which is proportional to magnitude of side peaks and dip in the transparency window
Yes
812
Sample under test has CDC equal to degenerate CDC

FIG. 8

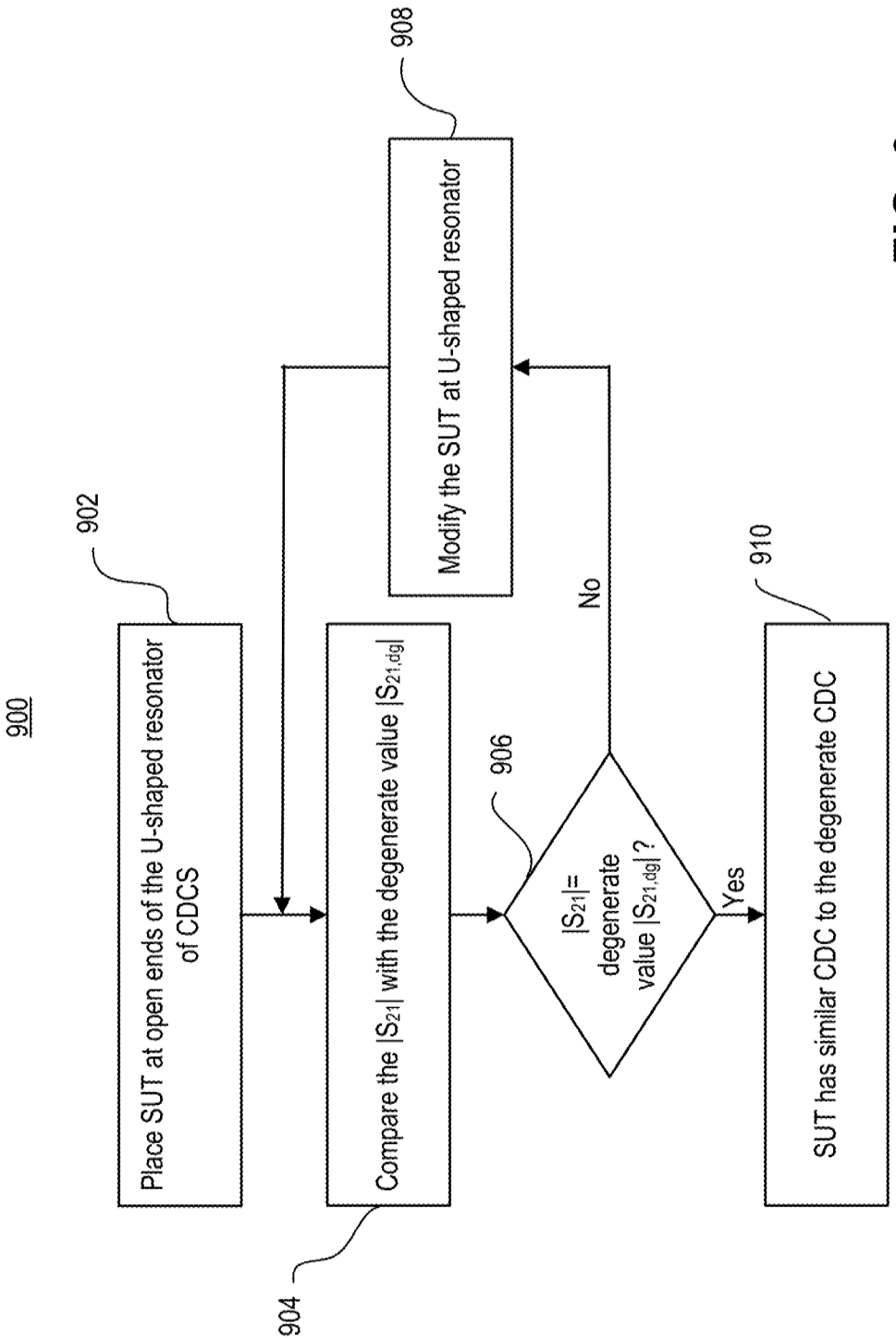

900
902
Place SUT at open ends of the U-shaped resonator of CDCS
904
Compare the |S21| with the degenerate value |S21,dg|
906
|S21|= degenerate value |S21,dg| ?
No
908
Modify the SUT at U-shaped resonator
Yes
910
SUT has similar CDC to the degenerate CDC

FIG. 9

COMPLEX DIELECTRIC CONSTANT SENSING SYSTEM AND METHOD

TECHNICAL FIELD

[0001] At least one embodiment is generally related to electronic sensing of one or more complex dielectric constants, and more particularly related to a system and method of complex dielectric constant sensing that may not apply a calibration of the system.

BACKGROUND

[0002] The retrieval of complex dielectric properties of materials such as substrates and thin films is a lengthy and tedious task. Especially during bulk fabrication, a significant amount of time is taken to characterize the complex dielectric properties of each substrate sample using the traditional techniques based on optical ellipsometry, transmission/reflection characteristics, cavity resonators, microwave based electrical impedance tomography (EIT) sensors, and other direct and indirect material characterization techniques. A family of sensors and sensing techniques that measure complex dielectric constants (CDCs) for material characterization, such as substrate samples, etc., are being used in various fields such as material science, biomedical engineering, manufacturing, and geophysics. But these sensors are large, have relatively lower sensitivity, consume relatively higher power, entail higher manufacturing cost, and use periodic calibration to maintain accuracy. These sensors may not work outside the optical spectrum and their use may be limited to bulk samples. And therefore, may not work on samples with arbitrary shapes and smaller volumes.

[0003] The background description provided here is for the purpose of generally presenting the context of the disclosure. Unless otherwise indicated here, the material described in this section is not prior art to the claims in this application and are not admitted to be prior art by inclusion in this section.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] At least one embodiment may be understood more fully from detailed description given below and from accompanying drawings, which, however, should not be taken to be limiting, but are for explanation and understanding.

[0005] FIG. **1**A illustrates a set of plots of dual electromagnetically induced transparency (EIT) bands that may be supported by the Complex Dielectric Constant Sensor (CDCS) at two distinct frequencies.

[0006] FIG. **1**B illustrates a Complex Dielectric Constant Sensing System (CDCSS), in accordance with at least one embodiment.

[0007] FIG. **2**A illustrates a structure of a CDCS, in accordance with at least one embodiment.

[0008] FIG. **2**B illustrates a structure of top layer of a CDCS comprising of open stubs based U-shaped resonator and a radial stub resonator of a CDCS, in accordance with at least one embodiment.

[0009] FIG. **3** illustrates three different lengths which determine resonance frequencies of open stubs of U-shaped resonator and a radial stub of a CDCS, in accordance with at least one embodiment.

[0010] FIG. **4**A illustrates a spectral response of a U-shaped resonator and a radial stub resonator of a CDCS along with the spectral transmission (S21) response of combined CDCS with both U-shaped and radial stub resonators, in accordance with at least one embodiment.

[0011] FIG. **4**B illustrates a magnitude and phase of transmission (S21) response of the CDCS, in accordance with at least one embodiment.

[0012] FIG. **4**C illustrates a surface charge density of the dual-band CDCS at the two distinct resonant frequencies, in accordance with at least one embodiment.

[0013] FIG. **5**A illustrates an embodiment wherein a Sample-Under-Test (SUT) is placed on the open stubs of a U-shaped resonator, in accordance with at least one embodiment.

[0014] FIG. **5**B illustrates a plot showing simulation results for a transmitted field (S21) spectrum because of variations in dielectric constant (Dk) of an SUT, when the SUT is placed on a U-shaped vertical stub, in accordance with at least one embodiment.

[0015] FIG. **5**C illustrates a plot showing the curve fitting model for the two distinct EIT bands due to variations in dielectric constant (Dk) of an SUT, when the SUT is placed on a U-shaped vertical stub, in accordance with at least one embodiment.

[0016] FIG. **6**A illustrates transmission characteristics (S21) of a CDCS at degenerate EIT band splitting point, when the SUT has a Dk equal to the degenerate Dk of the CDCS, in accordance with at least one embodiment.

[0017] FIG. **6**B illustrates transmission characteristics (S21) of a CDCS due to a slight variation in the Dk of an SUT, in accordance with at least one embodiment.

[0018] FIG. **6**C illustrates variation in the side peak amplitudes of the transmission spectrum (S21) due to slight variation in the Dk of an SUT, in accordance with at least one embodiment.

[0019] FIG. **7**A illustrates transmission characteristics (S21) of a CDCS at the degenerate EIT band splitting point due to a slight variation in the loss tangent of an SUT, when the Dk of the SUT is equal to the degenerate Dk, in accordance with at least one embodiment.

[0020] FIG. **7**B illustrates variation in the side peak amplitudes of the transmission spectrum (S21) due to a slight variation in the loss tangent of an SUT when the Dk of an SUT is equal to the degenerate Dk, in accordance with at least one embodiment.

[0021] FIG. **8** illustrates a flowchart of a CDC sensing method that determines whether the CDC of an SUT is approximately equal, within a certain tolerance, to the degenerate CDC or not, in accordance with at least one embodiment.

[0022] FIG. **9** illustrates a flowchart of a CDC characterization method of FIG. **5**A to characterize the value of the CDC of an SUT according to the known reference degenerate CDC, in accordance with at least one embodiment.

DETAILED DESCRIPTION

[0023] In at least one embodiment, a Complex Dielectric Constant Sensing System (CDCSS) comprises a Complex Dielectric Constant Sensor (CDCS) and related circuits. In at least one embodiment, CDCS may be based on dual Electromagnetically Induced Transparency (EIT) resonance based complex dielectric constant (CDC) comparator comprising two resonator structures, U-shaped resonator structure, and radial resonator structure, and a transmission line circuit that can characterize a dielectric material by com-

paring the transmission characteristics of a Sample-Under-Test (SUT) with the mode splitting degenerate EIT resonance response at a degenerate CDC. In at least one embodiment, CDCSS may allow for detecting the CDC of samples of arbitrary shapes and volumes including but not limited to substrate samples, thin films, antennas, and microwave devices. In at least one embodiment, CDCS can also be used for characterization of industrial dielectric materials including CDC characterization of substrate samples during the process of bulk fabrication.

[0024] In at least one embodiment, CDCS can characterize the CDC of an SUT. As such, changes in CDC due to a variation in the temperature are canceled because of the differential sensing; therefore, the calibration of sensors of system may not be required, which makes CDCS accurate, low power, and a real-time detector.

[0025] In the following description, numerous details are discussed to provide a more thorough explanation of embodiments of the present disclosure. It will be apparent, however, to one skilled in the art, that embodiments of the present disclosure may be practiced without these specific details. In other instances, well-known structures and devices are shown in block diagram form, rather than in detail, to avoid obscuring embodiments of the present disclosure.

[0026] Note that in the corresponding drawings of the embodiments, signals are represented with lines. Some lines may be thicker, to indicate more constituent signal paths, and/or have arrows at one or more ends, to indicate primary information flow direction. Such indications are not intended to be limiting. Rather, the lines are used in connection with one or more exemplary embodiments to facilitate easier understanding of a circuit or a logical unit. Any represented signal, as dictated by design needs or preferences, may actually comprise one or more signals that may travel in either direction, and may be implemented with any suitable type of signal scheme.

[0027] It is pointed out that those elements of the figures having the same reference numbers (or names) as the elements of any other figure can operate or function in any manner like that described but are not limited to such.

[0028] FIG. **1**A illustrates set of plots **100** of dual electromagnetically induced transparency (EIT) bands, EIT 1 **102** and EIT 2 **104**, at two distinct frequencies f_1 **124** and f_2 **126**, in accordance with at least one embodiment. FIG. **1**B illustrates a Complex Dielectric Constant Sensor System (CDCSS) **130**, in accordance with at least one embodiment. In at least one example, CDCSS **130** comprises Complex Dielectric Constant Sensor (CDCS) **150**, which includes sample-under-test (SUT) **106**, port **151**, stubs **152** and **153**, first resonator **154** (e.g., radial resonator), transmission line **155**, port **156**, second resonator **157** (e.g., U-shaped resonator), interconnect carrying output signal **161**, mixer **162**, interconnect carrying intermediate frequency signal f_{IF} **163**, Image Reject (IR) filter **164**, analog-to-digital converter (ADC) **166**, interconnect carrying digital signal **167**, digital processing unit **168** which includes power detection threshold **170**, memory **171**, display **172**, signal pre-processing **169**, first frequency synthesizer **174**, interconnect carrying oscillator signal f_o **175**, second frequency synthesizer **176**, and input frequency signal f_{IN} **177**.

[0029] In at least one embodiment, CDCSS **130** supports EIT 1 **102** and EIT 2 **104** at distinct frequencies f_1 **124** and f_2 **126**. In at least one embodiment, the CDCSS **150** exhibits resonance shifts in the EIT bands **102** and **104** from the unloaded response **110**, due to the presence of SUT **106** of different dielectric constants ϵ_{r1} **114**, ϵ_{r2} **112**, ϵ_{r3} **116**, and ϵ_{dg} **108**. In at least one embodiment, the two EIT modes **102** and **104** might become degenerate and merge at ϵ_{dg} **108**, when f_1 **124** becomes equal to f_2 **126**, that can cancel one another in the EIT band and may cause a dip in the spectrum **120** between two peaks **118** and **122**.

[0030] In at least one embodiment, CDCSS **150** determines whether the CDC value of an SUT is the same when compared with that of degenerate CDC ϵ_{dg} **108**. In at least one embodiment, first frequency synthesizer **174** generates oscillator signal f_o **175** in a first frequency range (e.g., 1.52 GHz to 3.52 GHZ). In at least one embodiment, second frequency synthesizer **176** generates input frequency signal f_{IN} **177** for dual EIT CDCS **160** in a second frequency range (e.g., 1.5 GHz to 3.5 GHZ). In at least one embodiment, the second frequency range may also contain frequency points at which CDC sensing is desired.

[0031] In at least one embodiment, dual EIT CDCS **160** compares CDC of SUT **106** with that of degenerate EIT ϵ_{dg} **108**. In at least one embodiment, output signal **161** is generated from dual EIT CDCS. In at least one embodiment, output signal **161** may be an attenuated and phase-shifted form of input signal f_{IN} **177**. In at least one embodiment, output signal **161** passes through transmission line **155** and is fed to mixer **162**.

[0032] In at least one embodiment, mixer **162** takes an RF signal from CDCS **160** and oscillator signal f_o **175** from first frequency synthesizer **174** as an input. In at least one embodiment, first frequency synthesizer **174** and second frequency synthesizer **176** are coupled with each other and produce a signal with a fixed offset of 20 MHz. In at least one embodiment, any offset frequency can be selected, but may be half of an ADC sampling frequency to meet the Nyquist sampling criteria. In at least one embodiment, mixer **162** produces an intermediate frequency signal f_{IN} **163** which comprises a sum and difference of input frequencies, and can be expressed as $f_{IN}=f_{IN}\pm fo$. In at least one embodiment, high frequency component of intermediate frequency signal f_{IN} **163** is filtered by IR filter **164** which produces low frequency analog signal **165**. In at least one embodiment, signal **165** has the same frequency as that of the offset between oscillator signal f_o **175** and input signal f_{IN} **177** from first frequency synthesizer **174** and second frequency synthesizer **176**, respectively.

[0033] In at least one embodiment, low frequency analog signal **165** (e.g., 20 MHz) may be converted to a digital signal using Analog to Digital Converter (ADC) **166** which produces digital signal **167**. In at least one embodiment, ADC **166** converts continuous physical quantities (e.g., voltages) to digital numbers that represent the amplitude of the physical quantities. In at least one embodiment, ADC **166** is one of: direct-conversion ADC (for flash ADC), two-step flash ADC, successive-approximation ADC (SAR ADC), ramp-compare ADC, Wilkinson ADC, integrating ADC, delta-encoded ADC or counter-ramp, pipeline ADC (also called subranging quantizer), sigma-delta ADC (also known as a delta-sigma ADC), time-interleaved ADC, ADC with intermediate FM stage, or time-stretch ADC. In at least one embodiment, sampling frequency of ADC **166** may be substantially twice than the frequency of low frequency analog signal **165**, thus meeting the Nyquist sampling criteria. In at least one embodiment, sampling frequency of

ADC **166** may be 40 MS/s which is twice the frequency of 20 MHz of low frequency analog signal **165**. In at least one embodiment, output of ADC **166** is provided to digital processing unit **168** for further processing.

[0034] In at least one embodiment, digital signal **167** may be processed in digital pre-processing block **169** which may be programmed to execute mathematical methods such as subsampling, antialiasing, filtering, and/or averaging. In at least one embodiment, digital pre-processing block **169** can be a Digital Signal Processor (DSP), an Application Specific Integrated Circuit (ASIC), a general-purpose Central Processing Unit (CPU), Graphics Processor Unit (GPU), or a low power logic implementing a finite state machine to perform the method of various embodiments, etc.

[0035] In at least one embodiment, memory **171** stores processed data in a format used by disclosed differential CDC sensing method. In at least one embodiment, memory **171** can include nonvolatile memory such that state does not change if the power to the memory device is interrupted, and/or volatile memory such that state is indeterminate if the power to the memory device is interrupted. In at least one embodiment, examples of nonvolatile memory include flash memory, magnetic memory, resistive memory, ferroelectric memory, etc. In at least one embodiment, examples of volatile memory include static random-access memory, dynamic random-access memory, etc. In at least one embodiment, memory **171** can store processed data, whether long-term or temporary, related to the execution of applications and functions of CDCSS **150**.

[0036] In at least one embodiment, memory **171** comprises a machine-readable media for storing computer-executable instructions (e.g., instructions to implement any other processes discussed herein). In at least one embodiment, machine-readable medium may include, but is not limited to, flash memory, optical disks, CD-ROMs, DVD ROMs, RAMS, EPROMs, EEPROMs, magnetic or optical cards, phase change memory (PCM), or other types of machine-readable media suitable for storing electronic or computer-executable instructions. At least one embodiment may be downloaded as a computer program (e.g., BIOS) which may be transferred from a remote computer (e.g., a server) to a requesting computer (e.g., a client) by way of data signals via a communication link (e.g., a modem or network connection).

[0037] In at least one embodiment, power detection and threshold block **170** detects a signal when crossing a certain predefined threshold to find a magnitude of degenerate mode split. In at least one embodiment, results are reported in a graph format on display unit **172**.

[0038] FIG. **2**A illustrates structure **200** of CDCS **160**, in accordance with at least one embodiment. In at least one embodiment, CDCS **160** comprises a transmission line **155** with U-shaped resonator **157** made of two symmetric rectangular vertical open stubs **152** and **153** with the same lengths and widths, and a radial resonator **154**. In at least one embodiment, structure **200** comprises of main transmission line **155** with two open stubs **152** and **153**, one radial stub **154**, and ports **151** and **156** (e.g., two matched RF ports). In at least one embodiment, stubs **152** and **153**, connected to the upper side of transmission line **155**, form a U-shaped resonator structure; and stub **154**, connected to the lower side of transmission line **155**, forms a radial resonator structure. In at least one embodiment, U-shaped structure comprising two stubs **152** and **153**, and a radial structure, when connected to opposite sides of transmission line **155**, but substantially at its center or middle point, makes a sensor.

[0039] In at least one embodiment, dual EIT based CDCS structure **200** may be implemented as a microstrip structure on a printed circuit board (PCB) at any scale depending on an operating frequency range and the desired degenerate CDC. In at least one embodiment, design parameters of structure **200** include PCBs' dielectric material, transmission line length t_l, transmission line width t_w, radial stub length l_r, radial stub arc length l_c, vertical stub length l_s, vertical stub width l_w, and distance between vertical stubs d. In at least one embodiment, two open stubs **152** and **153** are arranged across transmission line **155** in the form of U-shaped stub **157**. In at least one embodiment, U-shaped stub **157** comprising vertical open stubs **152** and **153**, is placed on one side of transmission line **155**. In at least one embodiment, radial stub **154** is placed on the opposite side of transmission line **155**. In at least one embodiment, since the length and width of vertical stubs and distance between two stubs is the same in U-shaped resonator, they resonate at the same frequency and produce an EIT resonance at that frequency. In at least one embodiment, radial stub **154** produces notch filter-like response. In at least one embodiment, the notch filter-like resonance field of the radial stub **154** interacts with the EIT resonance of the U-shaped stub **157** to produce two distinct EIT bands within the transmission spectrum. In at least one embodiment, at resonance, a strong electric field exists at open edges of U-shaped stub **157** and radial stub **154** which are then used for CDC sensing. In at least one embodiment, SUT **106** can be placed at the edges of two open stubs **152** and **153**.

[0040] FIG. **2**B illustrates top layer **250** of the CDCS structure **200** of FIG. **2**A. In at least one embodiment, the vertical open stubs **152** and **153** are placed on one side of transmission line **155** forming U-shaped stub **157**. In at least one embodiment, radial stub **154** is placed on the opposite side of transmission line **155**. In at least one embodiment, U-shaped stub **157** and radial stub **154** combine on opposite ends of transmission line **155** with two matched RF input and output ports **151** and **156** to form CDCS **160**.

[0041] FIG. **3** illustrates three configurations **300**, **320**, and **340**, respectively representing different lengths **310**, **330**, and **350** which determine the resonance frequencies of open stubs **152** and **153** of U-shaped resonator **157**, and radial stub resonator **154** of CDCS, in accordance with at least one embodiment. In at least one embodiment, three electrical lengths **310**, **330**, and **350** utilize part of U-shaped resonator **157**, radial resonator **154**, and transmission line **160** of FIG. **2**A. In at least one embodiment, electrical lengths determine the resonance frequencies of open-ended stubs **152** and **153**, and radial stub **154**. In at least one embodiment, small distance d as shown in FIG. **2**A, between two stubs makes a resonant U-shaped stub to constructively interfere in the EIT band. In at least one embodiment, stub **152** resonates at a frequency at which electrical distance **310** becomes one-fourth of the wavelength. In at least one embodiment, stubs **153** and **154** resonate at frequencies at which electrical distances **330** and **350** become one-fourth of wavelength, respectively. In at least one embodiment, electrical lengths are a function of an operating frequency band. In at least one embodiment, the radial stub resonates to give the notch a filter-like response. In at least one embodiment resonances of U-shaped stub and radial stub interfere to produce dual

EIT response. In at least one embodiment, the shape of the transmittance plot is due to combined transmittance response of the U-shaped structure and radial structure.

[0042] FIG. **4**A illustrates plot **400** showing spectral response of resonator components of CDCS **160**. In at least one embodiment, the radial stub resonator structure **410** with open radial stub **154** exhibits the characteristics of wideband notch filter **406** with dip **412**. In at least one embodiment, U-shaped resonator structure **408** shows EIT response **404** with EIT band 2 **104**. In at least one embodiment, the combined response **402** of U-shaped resonator **157** and radial stub resonator **154** forming CDCS **160** yields another response EIT 1 **102** in the EIT band due to the interaction of a notch filter response of a radial stub and the EIT response of a U-shaped stub along with dip **414** due to the notch filter response of the radial stub and EIT **104** due to a U-shaped resonator.

[0043] FIG. **4**B illustrates plot **430** showing the model simulation results of parameters like magnitude **402** and phase **432** response of CDCS **160**. In at least one embodiment, the CDCS **160** exhibits two distinct EIT bands **102** and **104**, and dip **414**. In at least one embodiment, first EIT band 1 **102** arises due to the destructive interference between radial stub **154** and U-shaped stub **157**. In at least one embodiment, second EIT band 2 **104**, arises due to the EIT response of U-shaped resonator **157**. In at least one embodiment, wideband notch response with dip **414** arises due to radial stub resonator **154**.

[0044] FIG. **4**C illustrates the interference pattern **470** observed in the surface charge density plots **472** and **474** due to EIT 1 **102** and EIT 2 **104** with color scale **480**. In at least one embodiment, U-shaped stub **157** and radial stub **154** possess out-of-phase charges which leads to two distinct EIT resonances within the transmission spectrum. In at least one embodiment, the interference of resonant responses of radial stub and U-shaped stub renders the medium transparent at a specific frequency due to the strong coupling between radial and U-shaped stubs making the way for potential sensing applications.

[0045] FIG. **5**A illustrates structure **500** showing CDCS **160** where an SUT **106** is placed on open stubs of U-shaped resonator **157**, in accordance with at least one embodiment. FIG. **5**A shows location where SUT may be placed on CDCS **160** in accordance with at least one embodiment. In at least one embodiment, SUT **106** may be placed on top of stubs **152** and **153**. In at least one embodiment, SUT may be placed at the open end of stubs where electric field distribution is strongest. In at least one embodiment, SUT placed on the top of stubs changes distribution of electric field based on value of its CDC. In at least one embodiment, when CDC value of an SUT is same as that of the degenerate CDC **108**, a mode splitting degenerate EIT resonance occurs with dip in the EIT band as a consequence of the destructive interference between EIT band, generated by U-shaped resonator, and the notch filter-like response, generated by radial stub resonator, which shows that an SUT has the same CDC as that of the degenerate CDC. Otherwise, in at least one embodiment, if CDCs of two samples are different, a dual EIT resonance is observed due to the interaction of the transmission field response of the radial and U-shaped stubs. In at least one embodiment, in case of a substrate sample, dual EIT resonance indicates that an SUT contains contamination or fabrication imperfections that may have changed its dielectric properties. In at least one embodiment, the mode splitting degenerate EIT resonance has a high sensitivity compared to that of a simple LC resonator that makes any changes in CDC easily distinguishable when mode splitting resonance is used. In at least one embodiment, CDCS can be compact and may not include power dividers or couplers. In at least one embodiment, high sensitivity of CDCS enables detection of disorders in the substrate fabrication, and the design of thin films, antennas and other microwave devices that require precise dielectric characterization. In at least one embodiment, since CDCs are compared based on the existence of a mode split in an EIT band, the visual inspection of a resonance curve can reveal results without complex data processing on recorded S21 parameter. In at least one embodiment, CDCS may not need calibration. As such, in at least one embodiment, CDCS may be cost-effective and easier to use in the field.

[0046] FIG. **5**B illustrates plot **530** showing simulation results for a transmitted field (S21) spectrum because of variations in the dielectric constant (Dk) to perform the characterization of CDCS, in accordance with at least one embodiment. Here, high/low transmittance in dB is shown on a gray scale **536** in which x-axis shows frequency and y-axis shows Dk of a sample. Plot **530** is a field plot of a CDCS due to variation in Dk of SUT **106**, in accordance with at least one embodiment. In this example, the transmission response exhibits high sensitivity **532** to the changes in the Dk of an SUT especially near the degenerate EIT band. In at least one embodiment, the frequency of mode splitting depends on the value of Dk of an SUT as indicated by plot **530**. In at least one embodiment the high sensitivity region is shown in inset **534**. In at least one embodiment, high sensitivity region **532** makes way for designing highly sensitive CDC sensors with CDC values in the vicinity of the degenerate CDC.

[0047] FIG. **5**C illustrates the plot showing a curve fitting model **570** comprising of two polynomial fitted contour plots for EIT bands EIT 1 **102** and EIT 2 **104** due to a variation in the Dk of an SUT. In FIG. **5**C, **572** shows the curve fitting model for EIT 1 **102** and **574** and curve fitting model for EIT 2 **104**. In at least one embodiment, curves **572** and **574** intersect each other within the high sensitivity region **532** at the mode splitting point **120**. The resonance frequency f_1 for contour plot of EIT 1 and f_2 for contour plot of EIT 2 may be given by:

$$f_1 = 0.00098657\epsilon_r^2 - 0.021811\epsilon_r + 2.272$$

$$f_2 = -0.0006979\epsilon_r^3 + 0.01771\epsilon_r^2 - 0.2126\epsilon_r + 2.915$$

[0048] In at least one embodiment, resonant shifts $df_1/d\epsilon_r$ and $df_2/d\epsilon_r$ in EIT bands EIT 1 and EIT 2 respectively, can be utilized to determine their spectral sensing sensitivity. In at least one embodiment, CDCS offers novel ultra-sensing due to its unique mode splitting approach. In at least one embodiment, the destructive interference between the responses of radial and U-shaped stubs makes CDCS highly suitable for detecting slight variations in the Dk of an SUT within the high sensitivity region **532**.

[0049] FIG. **6**A illustrates plot **600** showing the simulation results for a transmitted field (S21) spectrum of a CDCS with notch **414**, two peaks **118** and **122**, and dip **120** at degenerate CDC ϵ_{dg}. In at least one embodiment, the peak amplitudes a_1 and a_2 of EIT 1 **102** and EIT 2 **104** respectively

are symmetric at mode splitting CDC (e.g., $a_1/a_2=1$). Slight variation in CDC can make these amplitudes unequal causing CDCS to be highly sensitive to CDC variation. FIG. **6**B illustrates plot **630** showing results for transmitted field (S21) spectrums **632**, **634**, **636**, **638**, and **640** of CDCS at different Dk values which are slightly away from degenerate Dk ϵ_{dg}. In FIG. **6**B, a slight variation in Dk ($\Delta\epsilon=\epsilon_r-\epsilon_{dg}$) substantially changes peak amplitudes a_1 and a_2 to make them non-symmetric. This behavior can make CDCS a potential candidate for ultrasensitive sensing of the Dk of an SUT.

[0050] FIG. **6**C illustrates plot **670** depicting the effect of slight variations $\Delta\epsilon$ on the relative peak amplitude a_1/a_2. In at least one embodiment, variations in $\Delta\epsilon$ from −0.05 to +0.05 that constitute only ±1% change in a Dk can significantly alter relative peak amplitude a_1/a_2 from 1.55 to 0.55 that can cause CDCS to be highly suitable for ultrasensitive Dk sensing in the vicinity of ϵ_{dg}. In at least one embodiment, sensitivity of CDCS in terms of variation in a_1/a_2 due to a slight variation Ae can be represented as

$$d(a_1/a_2)/d(\Delta\epsilon) = 52.0640\Delta\epsilon - 10.04$$

[0051] FIG. **7**A illustrates plot **700** showing results for transmission coefficient (S21) spectrums **702**, **704**, **706**, **708**, **710**, **712**, and **714** of CDCS at different loss tangent tan (δ) values which are slightly away from the degenerate loss tangent value. In FIG. **7**A, a slight variation in tan (δ) substantially changes the magnitude of a split in the EIT band. In at least one embodiment, as tan (δ) increases, destructive interference between EIT bands becomes weaker that may result in a shallow split within the degenerate EIT band. This feature of CDCS can enable precise detection of the CDC of an SUT, in accordance with at least one embodiment.

[0052] FIG. **7**B illustrates plot **750** that depicts the effect of slight variations in tan (δ) on magnitude of dip in the transmission spectrum (S21) of CDCS. In an example embodiment, variations in tan (δ) can vary from 3.2×10^{-3} to 10^{-1} that can significantly alter the magnitude of a dip in the degenerate region from −32.8 dB to −6 dB that makes CDCS highly suitable for ultrasensitive CDC sensing in the vicinity of ϵ_{dg}.

[0053] FIG. **8** illustrates flowchart **800** of a CDC sensing method that determines whether the CDC of an SUT is the same, within a certain tolerance, as that of the degenerate mode splitting EIT or not, in accordance with at least one embodiment. While blocks are shown in a particular order, order can be modified. For example, some blocks may be performed before others and some blocks may be performed together or simultaneously. Blocks of flowchart **800** may be performed in hardware, software, or a combination of them.

[0054] In at least one embodiment, the magnitude of split in the EIT resonance band is used to quantize the difference of a CDC between an SUT and a degenerate CDC that is placed at the open ends of a U-shaped resonator. In at least one embodiment, at block **802**, SUT **106** is placed on a U-shaped resonator structure of CDCS **160** mounted on the top of stubs as shown in FIG. **5**A.

[0055] In at least one embodiment, at block **804**, presence or absence of a mode split within EIT transparency window is detected by coarse scanning dual EIT bands with a frequency step size Δf_{coarse} (e.g., 1 MHz). In at least one embodiment, a large step size is used to reduce scanning time in the bandwidth of interest. In at least one embodiment, step size of 1 MHz and frequency of interest 1.5 GHz to 3.5 GHz are example use cases and may be changed as needed. In at least one embodiment, at block **806**, if it is determined that an EIT mode split does not exist, then at block **814** the conclusion is that SUT **106** has a different CDC as compared to the degenerate CDC. In at least one embodiment, if the split is detected at block **806**, then the next processing starts at block **808**. In at least one embodiment, magnitude and frequency of side peaks and split in the EIT band is quantized by the fine scanning step of Δf_{fine} (e.g., 10 KHz) at block **808** and the magnitude of transmission spectrum $|S_{21}|$ is compared to the magnitude of the transmission spectrum at the degenerate CDC value $|S_{21,dg}|$.

[0056] In at least one embodiment, scanning window at block **808** may be limited to that frequency window in which the mode split is detected, and this significantly reduces the total scan time even with a smaller frequency step. In at least one embodiment, if the magnitude of a transmission spectrum is the same as that of the degenerate transmission spectrum at block **810**, SUT **106** can have an equivalent CDC as that of the degenerate CDC at block **812**. In at least one embodiment, if the magnitude of S21 is different than that of the degenerate value $|S_{21,dg}|$, the difference in magnitude of side peaks and the dip in the transparency window of an SUT and the degenerate CDC may be computed at block **816** which may be proportional to a difference in the CDC of an SUT and the degenerate CDC.

[0057] FIG. **9** illustrates flowchart **900** of a CDC sensing method of FIG. **5**A to characterized the CDC of an SUT with the known reference CDC, in accordance with at least one embodiment. While blocks are shown in a particular order, order can be modified. For example, some blocks may be performed before others and some blocks may be performed together or simultaneously. Blocks of flowchart **900** may be performed by hardware, software, or a combination of them.

[0058] In at least one embodiment, at block **902**, SUT **106** is placed on top of stubs of U-shaped resonator structure of a CDCS. In at least one embodiment, at block **904**, magnitude of S_{21} **906** is compared with the corresponding magnitude in case of reference degenerate CDC. In at least one embodiment, magnitude of side peaks surrounding the dip within the degenerate EIT band may be a function of a difference in the Dk values of an SUT **106** and a reference CDC. In at least one embodiment, the magnitude of dip within degenerate EIT band may be a function of a difference in tan (δ) values of SUT **106** and the reference CDC. In at least one embodiment, if Dk or tan (δ) or both of SUT are the same as that of the corresponding Dk and tan (δ) of degenerate CDC based on the comparison of magnitude of S_{21} with $S_{21,dg}$ at block **906**, CDCS can generate a sharp mode splitting resonance within the degenerate EIT resonance; as a result, the SUT may have approximately the same CDC as that of the reference degenerate CDC determined at block **910**. In at least one embodiment, if Dk or tan (δ) or both of SUT are not the same as the corresponding Dk and tan (δ) of the degenerate CDC based on the comparison of magnitude of S_{21} with $S_{21,dg}$ at block **906**, then SUT **106** that need to be modified and SUT with different dielectric constant is placed block **908**; and the magnitude of S_{21} **904** is compared with the degenerate value $|S_{21,dg}|$ again at block **904**. In at least one embodiment, blocks **904** and **908** are

iterated until the magnitudes of S_{21} and $S_{21,dg}$ become same. In at least one embodiment, CDC of SUT **106** may be approximately the same as of that reference degenerate CDC at which mode splitting is observed within the degenerate EIT band.

[0059] Here, "device" may generally refer to an apparatus according to context of usage of that term. In at least one embodiment, a device may refer to a stack of layers or structures, a single structure or layer, a connection of various structures having active and/or passive elements, etc. Generally, a device is a three-dimensional structure with a plane along x-y direction and a height along z direction of an x-y-z Cartesian coordinate system. In at least one embodiment, plane of device may also be plane of an apparatus, which comprises device.

[0060] Throughout specification, and in claims, "connected" may generally refer to a direct connection, such as electrical, mechanical, or magnetic connection between things that are connected, without any intermediary devices.

[0061] Here, "coupled" may generally refer to a direct or indirect connection, such as a direct electrical, mechanical, or magnetic connection between things that are connected or an indirect connection, through one or more passive or active intermediary devices.

[0062] Here, "adjacent" may generally refer to a position of a thing being next to (e.g., immediately next to or close to with one or more things between them) or adjoining another thing (e.g., abutting it).

[0063] Here, "circuit" or "module" may generally refer to one or more passive and/or active components that are arranged to cooperate with one another to provide a desired function.

[0064] Here, "signal" may generally refer to at least one current signal, voltage signal, magnetic signal, or data/clock signal. Here, meaning of "a," "an," and "the" include plural references. Here, meaning of "in" includes "in" and "on."

[0065] Here, "analog signal" generally refers to any continuous signal for which time varying feature (variable) of signal is a representation of some other time varying quantity, e.g., analogous to another time varying signal.

[0066] Here, "digital signal" may generally refer to a physical signal that is a representation of a sequence of discrete values (a quantified discrete-time signal), for example of an arbitrary bit stream, or of a digitized (sampled and analog-to-digital converted) analog signal.

[0067] Here, "scaling" may generally refer to converting a design (schematic and layout) from one process technology to another process technology and subsequently being reduced in layout area. Here, "scaling" may generally refer to downsizing layout and devices within same technology node. Here, "scaling" may also generally refer to adjusting (e.g., slowing down or speeding up—e.g., scaling down, or scaling up respectively) of a signal frequency relative to another parameter, for example, power supply level.

[0068] Here, terms "substantially," "close," "approximately," "near," and "about," generally refer to being within +/−10% of a target value. For example, unless otherwise specified in explicit context of their use, terms "substantially equal," "about equal" and "approximately equal" mean that there is no more than incidental variation between among things so described. In at least one embodiment, such variation is typically no more than +/−10% of a predetermined target value.

[0069] Unless otherwise specified use of ordinal adjectives "first," "second," and "third," etc., to describe a common object, merely indicate that different instances of like objects are being referred to and are not intended to imply that objects so described must be in a given sequence, either temporally, spatially, in ranking or in any other manner.

[0070] For purposes of present disclosure, phrases "A and/or B" and "A or B" mean (A), (B), or (A and B). In at least one embodiment, phrase "A, B, and/or C" means (A), (B), (C), (A and B), (A and C), (B and C), or (A, B and C).

[0071] Here, "left," "right," "front," "back," "top," "bottom," "over," "under," and like in description and in claims, if any, are used for descriptive purposes and not necessarily for describing permanent relative positions. In at least one embodiment, "over," "under," "front side," "back side," "top," "bottom," "over," "under," and "on" as used herein refer to a relative position of one component, structure, or material with respect to other referenced components, structures or materials within a device, where such physical relationships are noteworthy. In at least one embodiment, these terms are employed herein for descriptive purposes only and predominantly within context of a device z-axis and therefore may be relative to an orientation of a device. In at least one embodiment, a first material "over" a second material in context of a figure provided herein may also be "under" second material if device is oriented upside-down relative to context of figure provided. In context of materials, one material disposed over or under another may be directly in contact or may have one or more intervening materials. Moreover, one material disposed between two materials may be directly in contact with two layers or may have one or more intervening layers. In at least one embodiment, a first material "on" a second material is in direct contact with that second material. Similar distinctions are to be made in context of component assemblies.

[0072] Here, "between" may be employed in context of z-axis, x-axis, or y-axis of a device. In at least one embodiment, a material that is between two other materials may be in contact with one or both of those materials, or may be separated from both of other two materials by one or more intervening materials. In at least one embodiment, a material "between" two other materials may therefore be in contact with either of other two materials, or may be coupled to other two materials through an intervening material. In at least one embodiment, a device that is between two other devices may be directly connected to one or both of those devices, or may be separated from both of other two devices by one or more intervening devices.

[0073] Reference in specification to "an embodiment," "one embodiment," "in at least one embodiment," "some embodiments," or "other embodiments" means that a particular feature, structure, or characteristic described in connection with embodiments is included in at least some embodiments, but not necessarily all embodiments. Various appearances of "an embodiment," "one embodiment," "in at least one embodiment," or "some embodiments" are not necessarily all referring to same embodiments. If specification states a component, feature, structure, or characteristic "may," "might," or "could" be included, that particular component, feature, structure, or characteristic is not required to be included. If specification or claim refers to "a" or "an" element, that does not mean there is only one of

elements. If specification or claims refer to "an additional" element, that does not preclude there being more than one of additional elements.

[0074] Furthermore, particular features, structures, functions, or characteristics may be combined in any suitable manner in one or more embodiments. For example, a first embodiment may be combined with a second embodiment anywhere particular features, structures, functions, or characteristics associated with two embodiments are not mutually exclusive.

[0075] While at least one embodiment has been described in conjunction with specific embodiments thereof, many alternatives, modifications and variations of such embodiments will be apparent to those of ordinary skill in the art considering description herein. At least one embodiment is intended to embrace all such alternatives, modifications, and variations as to fall within broad scope of appended claims.

[0076] In addition, well-known power/ground connections to integrated circuit (IC) chips and other components may or may not be shown within presented figures, for simplicity of illustration and discussion, and so as not to obscure any embodiment. Further, arrangements may be shown in block diagram form to avoid obscuring any embodiment, and in view of the fact that specifics with respect to implementation of such block diagram arrangements are highly dependent upon the platform within which an embodiment is to be implemented (e.g., such specifics should be well within purview of one skilled in art). Where specific details (e.g., circuits) are set forth to describe example embodiments of disclosure, it should be apparent to one skilled in art that disclosure can be practiced without, or with variation of, these specific details. Description of an embodiment is thus to be regarded as illustrative instead of limiting.

[0077] In at least one embodiment, structures described herein can also be described as method(s) of forming those structures or apparatuses, and method(s) of operation of these structures or apparatuses. Following examples are provided that illustrate at least one embodiment. An example can be combined with any other example. As such, at least one embodiment can be combined with at least another embodiment without changing scope of an embodiment.

[0078] Example 1 is an apparatus comprising: a transmission line comprising a rectangular-shaped microstrip; a first resonator coupled in a perpendicular position relative to the transmission line; a second resonator comprising of two symmetric and rectangular-shaped body sections with substantially equal width and length, placed substantially in a middle of the transmission line and in a mirror position relative to the first resonator; and a region for a sample-under-test, wherein the region is coupled to the first resonator.

[0079] Example 2 is an apparatus according to any examples herein, in particular example 1, wherein the first resonator comprises an open circuit vertical U-shaped resonator.

[0080] Example 3 is an apparatus according to any examples herein, in particular example 1, wherein the second resonator comprises a radial stub resonator.

[0081] Example 4 is an apparatus according to any examples herein, in particular example 1, wherein the first resonator and the second resonator are to generate two EIT peaks at different frequencies for complex dielectric constant and loss tangent (tan(δ)) sensing.

[0082] Example 5 is an apparatus according to any examples herein, in particular example 1, wherein the first resonator and the second resonator are to generate a mode splitting within a degenerate electromagnetically induced transparency band, wherein to generate the mode splitting, a complex dielectric constant of the sample-under-test is to substantially match a specific value.

[0083] Example 6 is an apparatus according to any examples herein, in particular example 1, wherein in an absence of the sample-under-test, the first resonator and the second resonator are to generate two distinct electromagnetically induced transparency based resonance fields.

[0084] Example 7 is an apparatus according to any examples herein, in particular example 1, wherein the first resonator and the second resonator are independent of calibration.

[0085] Example 8 is an apparatus according to any examples herein, in particular example 1, wherein the first resonator and second resonator are to sense a dielectric loss tangent (tan(δ)) of the sample-under-test.

[0086] Example 9 is an apparatus according to any examples herein, in particular example 1, wherein the first resonator and the second resonator are to sense a permittivity of the sample-under-test and have a linear sensitivity to a variation in side peak amplitudes (a_1/a_2).

[0087] Example 10 is an apparatus according to any examples herein, in particular example 1, wherein the first resonator and the second resonator have a non-linear sensitivity to a variation in a magnitude of a dip, wherein the dip is associated with mode splitting.

[0088] Example 11 is an apparatus according to any examples herein, in particular example 1, wherein the first resonator and the second resonator are on a printed circuit board.

[0089] Example 12 is an apparatus according to any examples herein, in particular example 1, further comprising: a mixer coupled to the transmission line; a first frequency synthesizer coupled to the mixer; a second frequency synthesizer coupled to the transmission line; an IR filter coupled to an output of the mixer; an analog-to-digital converter coupled to an output of the IR filter; and a processing module coupled to an output of the analog-to-digital converter.

[0090] Example 13 is method comprising: deploying a sample-under-test on a first resonator coupled to a second resonator, wherein the first resonator and the second resonator provide a first output via a transmission line; mixing the first output with an oscillator frequency to generate a second output; filtering the second output to generate an analog output; converting the analog output to a digital output; and analyzing the digital output to determine whether a complex dielectric constant of the sample-under-test is same as a degenerate complex dielectric constant that causes mode splitting.

[0091] Example 14 is a method according to any examples herein, in particular example 13, wherein analyzing the digital output comprises: determining whether electromagnetically induced transparency based resonance field from the transmission line exhibits two distinct electromagnetically induced transparency modes; and notifying that the sample-under-test has a different complex dielectric constant than the degenerate complex dielectric constant if the elec-

tromagnetically induced transparency based resonance field exhibits two distinct electromagnetically induced transparency modes.

[0092] Example 15 is a method according to any examples herein, in particular example 13, wherein analyzing the digital output comprises: determining whether electromagnetically induced transparency based resonance field from the transmission line exhibits the mode splitting within a degenerate electromagnetically induced transparency band; determining, based on exhibition of the mode splitting, a first magnitude of a first side peak in a transmission spectrum surrounding a mode splitting point; determining, based on exhibition of the mode splitting, a second magnitude of a second side peak in the transmission spectrum surrounding the mode splitting point; comparing the first magnitude with the second magnitude; and notifying, based on the comparing, if the first magnitude and the second magnitude are unequal, that the sample-under-test has a different dielectric constant than the degenerate complex dielectric constant associated with the mode splitting point.

[0093] Example 16 is a method according to any examples herein, in particular example 13, wherein analyzing the digital output comprises: determining whether electromagnetically induced transparency based resonance field from the transmission line exhibits the mode splitting within a degenerate electromagnetically induced transparency band; determining, based on exhibition of the mode splitting, a first magnitude of a dip in a transmission spectrum of the sample-under-test; determining a second magnitude of a second dip associated with the degenerate complex dielectric constant; comparing the first magnitude with the second magnitude; and notifying that the sample-under-test has a different loss tangent if the first magnitude is unequal to the second magnitude based on the comparing.

[0094] Example 17 is a method according to any examples herein, in particular example 13, wherein analyzing the digital output comprises: determining whether electromagnetically induced transparency based resonance field from the transmission line exhibits the mode splitting within a degenerate electromagnetically induced transparency band; determining a first magnitude of a first side peak in a transmission spectrum surrounding a mode splitting point; determining a second magnitude of a second side peak in the transmission spectrum surrounding the mode splitting point; determining a third magnitude of a first dip in the transmission spectrum of the sample-under-test; determining a fourth magnitude of a second dip associated with the degenerate complex dielectric constant; performing a first comparison between the first magnitude with the second magnitude; performing a second comparison the third magnitude with the fourth magnitude; and notifying, based on the first comparison and the second comparison, if the first comparison indicates that the first magnitude is substantially equal to the second magnitude and if the second comparison indicates that the third magnitude and the fourth magnitude are substantially equal, that the sample-under-test has the same complex dielectric constant as the degenerate complex dielectric constant that causes the mode splitting.

[0095] Example 18 is a method according to any examples herein, in particular example 13, wherein the first resonator comprises an open circuit vertical U-shaped resonator, and wherein the second resonator comprises a radial stub resonator.

[0096] Example 19 is a method according to any examples herein, in particular example 13, wherein the first resonator and the second resonator have a non-linear sensitivity to a variation in a magnitude of a dip, wherein the dip is associated with the mode splitting.

[0097] Example 20 is a system comprises: a transmission line comprising a rectangular-shaped microstrip; a first resonator coupled in a perpendicular position relative to the transmission line; a second resonator comprising of two symmetric and rectangular-shaped body sections with substantially equal width and length, placed substantially in a middle of the transmission line and in a mirror position relative to the first resonator; a region for a sample-under-test, wherein the region is coupled to the first resonator; a mixer coupled to the transmission line; a first frequency synthesizer coupled to the mixer; a second frequency synthesizer coupled to the transmission line; an IR filter coupled to an output of the mixer; an analog-to-digital converter coupled to an output of the IR filter; and a processing module coupled to an output of the analog-to-digital converter.

[0098] An abstract is provided that will allow reader to ascertain the nature and the gist of technical disclosure. An Abstract is submitted with an understanding that it will not be used to limit scope or meaning of claims. Following claims are hereby incorporated into detailed description, with each claim standing on its own as a separate embodiment.

We claim:

1. An apparatus comprising:

a transmission line comprising a rectangular-shaped microstrip;

a first resonator coupled in a perpendicular position relative to the transmission line;

a second resonator comprising of two symmetric and rectangular-shaped body sections with substantially equal width and length, placed substantially in a middle of the transmission line and in a mirror position relative to the first resonator; and

a region for a sample-under-test, wherein the region is coupled to the first resonator.

2. The apparatus of claim **1**, wherein the first resonator comprises an open circuit vertical U-shaped resonator.

3. The apparatus of claim **1**, wherein the second resonator comprises a radial stub resonator.

4. The apparatus of claim **1**, wherein the first resonator and the second resonator are to generate two EIT peaks at different frequencies for complex dielectric constant and loss tangent (tan(δ)) sensing.

5. The apparatus of claim **1**, wherein the first resonator and the second resonator are to generate a mode splitting within a degenerate electromagnetically induced transparency band, wherein to generate the mode splitting, a complex dielectric constant of the sample-under-test is to substantially match a specific value.

6. The apparatus of claim **1**, wherein in an absence of the sample-under-test, the first resonator and the second resonator are to generate two distinct electromagnetically induced transparency based resonance fields.

7. The apparatus of claim **1**, wherein the first resonator and the second resonator are independent of calibration.

8. The apparatus of claim **1**, wherein the first resonator and second resonator are to sense a dielectric loss tangent (tan(δ)) of the sample-under-test.

9. The apparatus of claim 1, wherein the first resonator and the second resonator are to sense a permittivity of the sample-under-test and have a linear sensitivity to a variation in side peak amplitudes (a_1/a_2).

10. The apparatus of claim 1, wherein the first resonator and the second resonator have a non-linear sensitivity to a variation in a magnitude of a dip, wherein the dip is associated with mode splitting.

11. The apparatus of claim 1, wherein the first resonator and the second resonator are on a printed circuit board.

12. The apparatus of claim 1 further comprising:

a mixer coupled to the transmission line;

a first frequency synthesizer coupled to the mixer;

a second frequency synthesizer coupled to the transmission line;

an IR filter coupled to an output of the mixer;

an analog-to-digital converter coupled to an output of the IR filter; and

a processing module coupled to an output of the analog-to-digital converter.

13. A method comprising:

deploying a sample-under-test on a first resonator coupled to a second resonator, wherein the first resonator and the second resonator provide a first output via a transmission line;

mixing the first output with an oscillator frequency to generate a second output;

filtering the second output to generate an analog output;

converting the analog output to a digital output; and

analyzing the digital output to determine whether a complex dielectric constant of the sample-under-test is same as a degenerate complex dielectric constant that causes mode splitting.

14. The method of claim 13, wherein analyzing the digital output comprises:

determining whether electromagnetically induced transparency based resonance field from the transmission line exhibits two distinct electromagnetically induced transparency modes; and

notifying that the sample-under-test has a different complex dielectric constant than the degenerate complex dielectric constant if the electromagnetically induced transparency based resonance field exhibits two distinct electromagnetically induced transparency modes.

15. The method of claim 13, wherein analyzing the digital output comprises:

determining whether electromagnetically induced transparency based resonance field from the transmission line exhibits the mode splitting within a degenerate electromagnetically induced transparency band;

determining, based on exhibition of the mode splitting, a first magnitude of a first side peak in a transmission spectrum surrounding a mode splitting point;

determining, based on exhibition of the mode splitting, a second magnitude of a second side peak in the transmission spectrum surrounding the mode splitting point;

comparing the first magnitude with the second magnitude; and

notifying, based on the comparing, if the first magnitude and the second magnitude are unequal, that the sample-under-test has a different dielectric constant than the degenerate complex dielectric constant associated with the mode splitting point.

16. The method of claim 13, wherein analyzing the digital output comprises:

determining whether electromagnetically induced transparency based resonance field from the transmission line exhibits the mode splitting within a degenerate electromagnetically induced transparency band;

determining, based on exhibition of the mode splitting, a first magnitude of a dip in a transmission spectrum of the sample-under-test;

determining a second magnitude of a second dip associated with the degenerate complex dielectric constant;

comparing the first magnitude with the second magnitude; and

notifying that the sample-under-test has a different loss tangent if the first magnitude is unequal to the second magnitude based on the comparing.

17. The method of claim 13, wherein analyzing the digital output comprises:

determining whether electromagnetically induced transparency based resonance field from the transmission line exhibits the mode splitting within a degenerate electromagnetically induced transparency band;

determining a first magnitude of a first side peak in a transmission spectrum surrounding a mode splitting point;

determining a second magnitude of a second side peak in the transmission spectrum surrounding the mode splitting point;

determining a third magnitude of a first dip in the transmission spectrum of the sample-under-test;

determining a fourth magnitude of a second dip associated with the degenerate complex dielectric constant;

performing a first comparison between the first magnitude with the second magnitude;

performing a second comparison the third magnitude with the fourth magnitude; and

notifying, based on the first comparison and the second comparison, if the first comparison indicates that the first magnitude is substantially equal to the second magnitude and if the second comparison indicates that the third magnitude and the fourth magnitude are substantially equal, that the sample-under-test has the same complex dielectric constant as the degenerate complex dielectric constant that causes the mode splitting.

18. The method of claim 13, wherein the first resonator comprises an open circuit vertical U-shaped resonator, and wherein the second resonator comprises a radial stub resonator.

19. The method of claim 13, wherein the first resonator and the second resonator have a non-linear sensitivity to a variation in a magnitude of a dip, wherein the dip is associated with the mode splitting.

20. A system comprising:

a transmission line comprising a rectangular-shaped microstrip;

a first resonator coupled in a perpendicular position relative to the transmission line;

a second resonator comprising of two symmetric and rectangular-shaped body sections with substantially equal width and length, placed substantially in a middle of the transmission line and in a mirror position relative to the first resonator;

a region for a sample-under-test, wherein the region is coupled to the first resonator;
a mixer coupled to the transmission line;
a first frequency synthesizer coupled to the mixer;
a second frequency synthesizer coupled to the transmission line;
an IR filter coupled to an output of the mixer;
an analog-to-digital converter coupled to an output of the IR filter; and
a processing module coupled to an output of the analog-to-digital converter.

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