US010261032B2

(12) **United States Patent**
Orloff et al.

(10) **Patent No.: US 10,261,032 B2**
(45) **Date of Patent: Apr. 16, 2019**

(54) **NONCONTACT RESONAMETER, PROCESS FOR MAKING AND USE OF SAME**

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(72) Inventors: **Nathan Daniel Orloff**, Boulder, CO (US); **Christian John Long**, Greenbelt, MD (US); **Jan Obrzut**, Germantown, MD (US)

(73) Assignee: **NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY**, Washington, DC (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 413 days.

(21) Appl. No.: **14/958,539**

(22) Filed: **Dec. 3, 2015**

(65) **Prior Publication Data**

US 2016/0161424 A1 Jun. 9, 2016

Related U.S. Application Data

(60) Provisional application No. 62/086,748, filed on Dec. 3, 2014.

(51) **Int. Cl.**
G01N 22/04 (2006.01)
G01N 33/543 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***G01N 22/00*** (2013.01)

(58) **Field of Classification Search**
CPC G01N 22/00; G01N 22/04; G01N 33/543; G01N 33/557; G01R 27/04; G01R 27/32;
(Continued)

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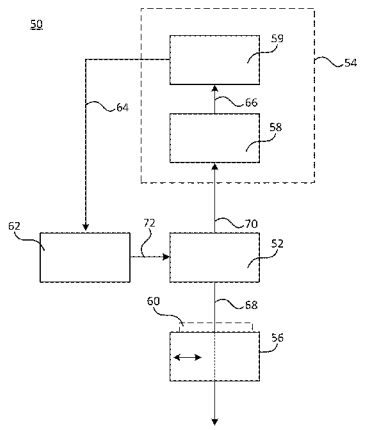
Primary Examiner — Neel D Shah
(74) *Attorney, Agent, or Firm* — Office of Chief Counsel for National Institute of Standards and Technology

(57) **ABSTRACT**

A noncontact resonameter includes: a resonator to: produce an excitation signal including a field; subject a sample to the excitation signal; produce a first resonator signal in a presence of the sample and the excitation signal, the first resonator signal including: a first quality factor of the resonator; a first resonance frequency of the resonator; or a combination thereof, the first resonator signal occurring in an absence of contact between the sample and the resonator; and produce a second resonator signal in a presence of the excitation signal and an absence of the sample, the second resonator signal including: a second quality factor of the resonator; a second resonance frequency of the resonator; or a combination thereof; a circuit in electrical communication with the resonator to receive the first resonator signal and the second resonator signal; and a continuous feeder to: provide the sample proximate to the resonator; dispose the sample intermediately in the field of the excitation signal during production of the first resonator signal; remove the sample from the resonator; and manipulate a position of the sample relative to the resonator in a continuous motion and in an absence of contact between the sample and the resonator.

16 Claims, 26 Drawing Sheets



(51) **Int. Cl.**

G01N 33/557	(2006.01)
G01R 27/04	(2006.01)
G01R 27/32	(2006.01)
G01V 3/00	(2006.01)
G01R 33/28	(2006.01)
G01R 33/32	(2006.01)
G01R 33/46	(2006.01)
G01R 33/60	(2006.01)
G01R 33/62	(2006.01)
G01R 33/34	(2006.01)
G01N 22/00	(2006.01)

(58) **Field of Classification Search**
CPC G01R 33/28; G01R 33/32; G01R 33/46; G01R 33/60; G01R 33/62; G01R 33/341; G01R 33/343; G01V 3/00
See application file for complete search history.

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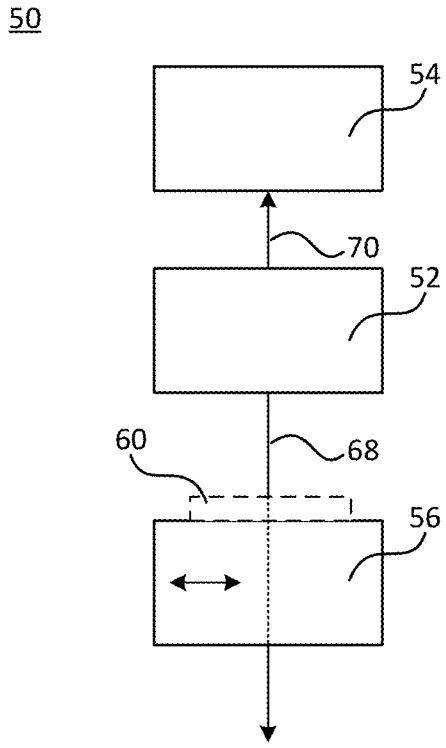
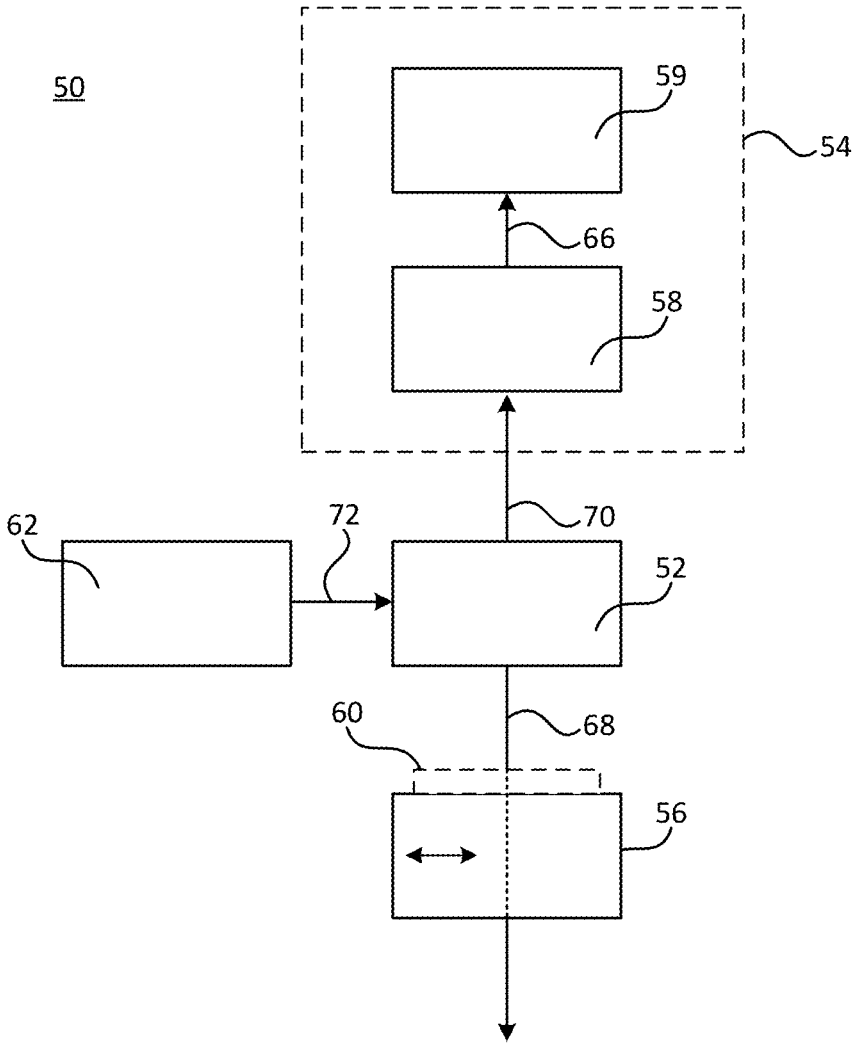


FIG. 1



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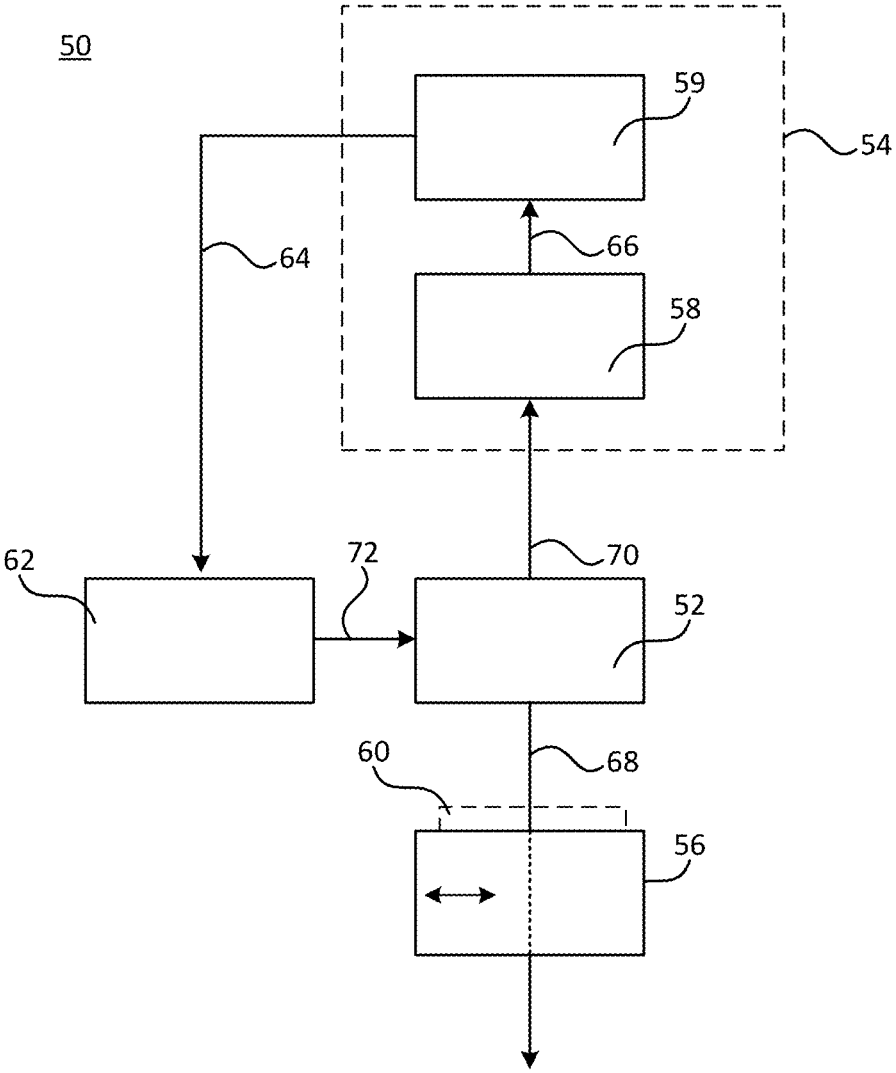

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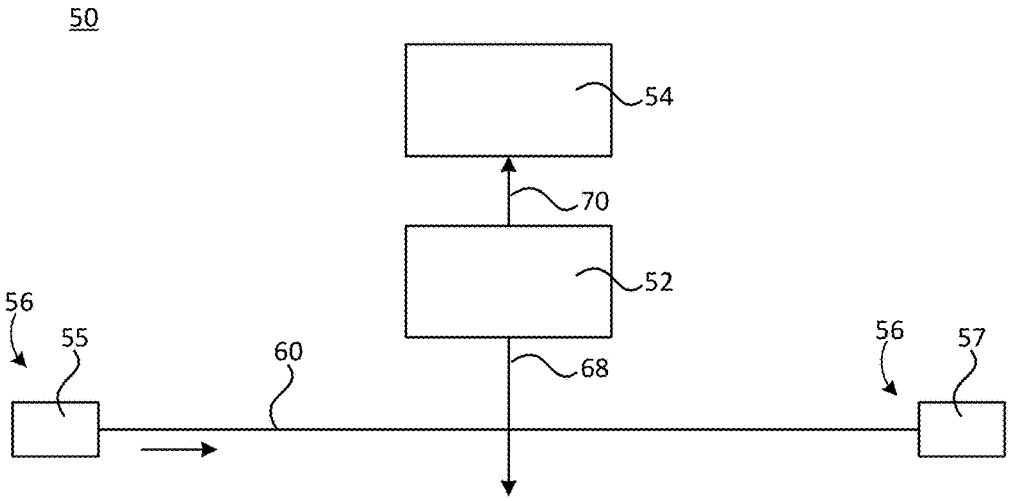
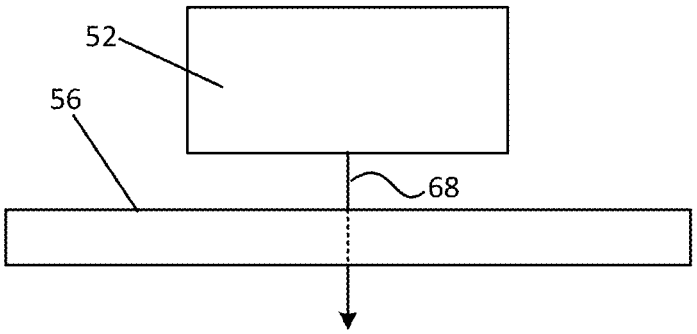


FIG. 4



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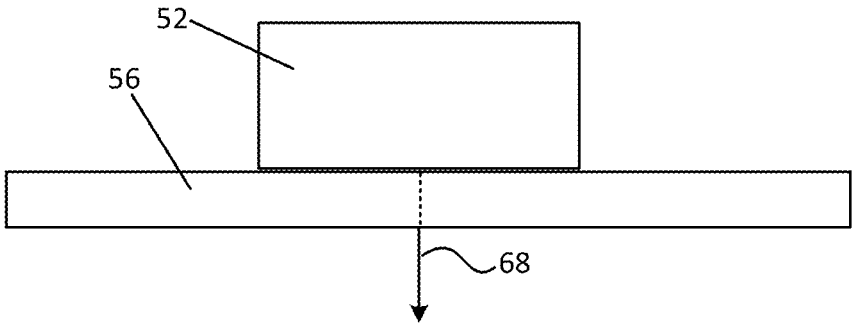

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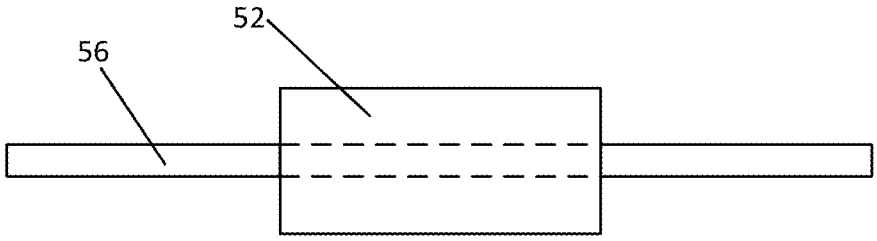

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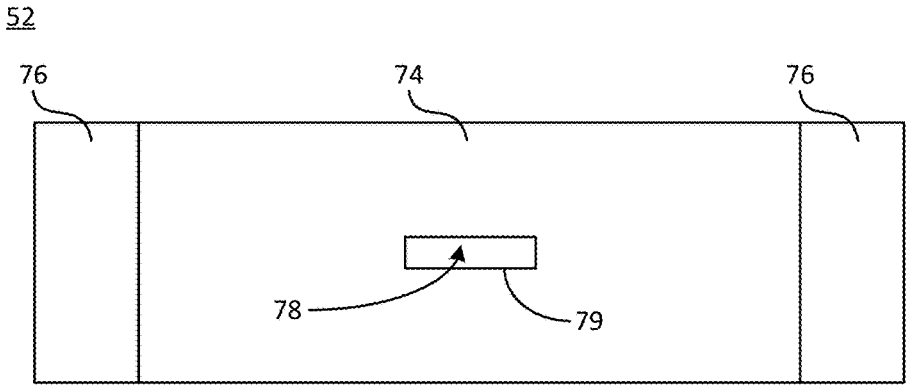

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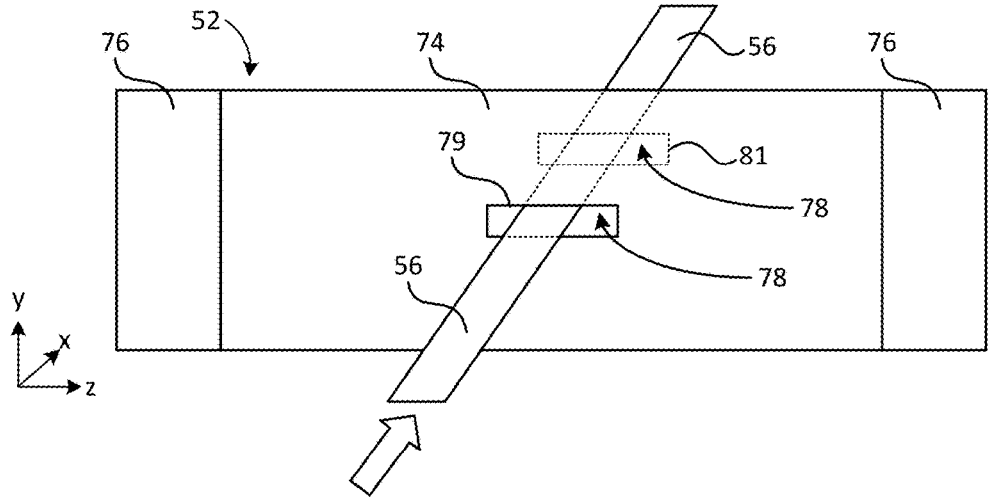

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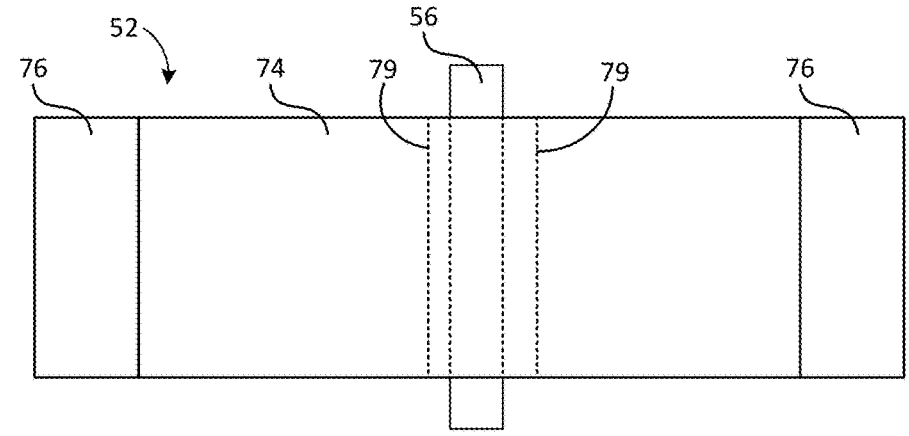
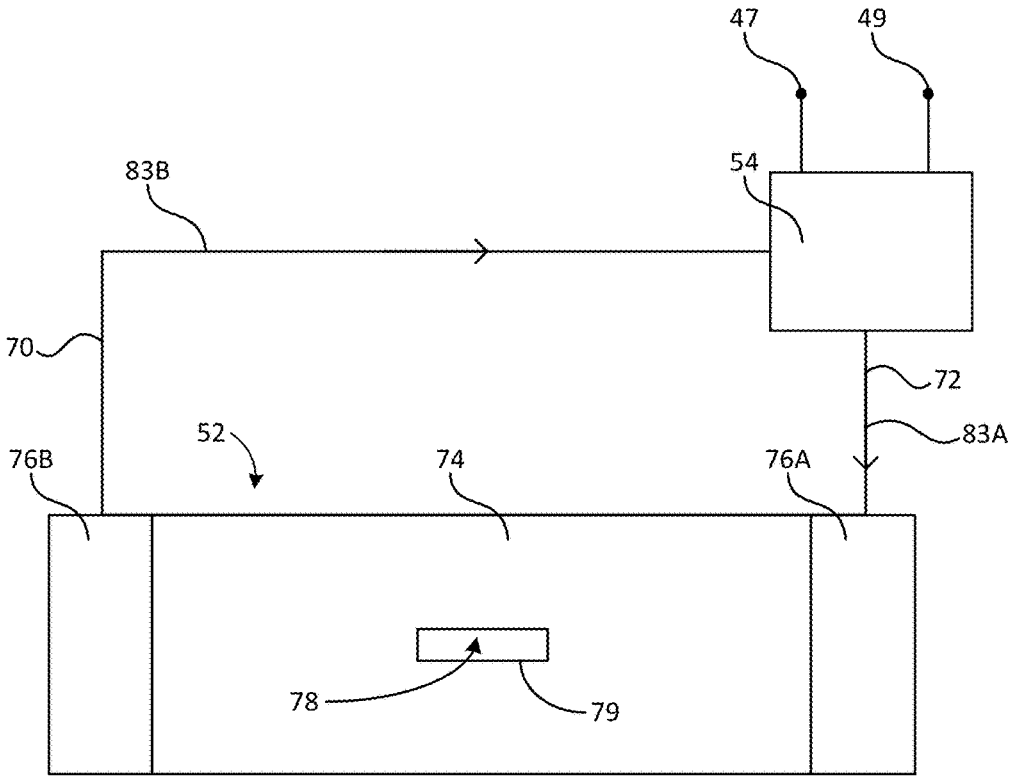


FIG. 10



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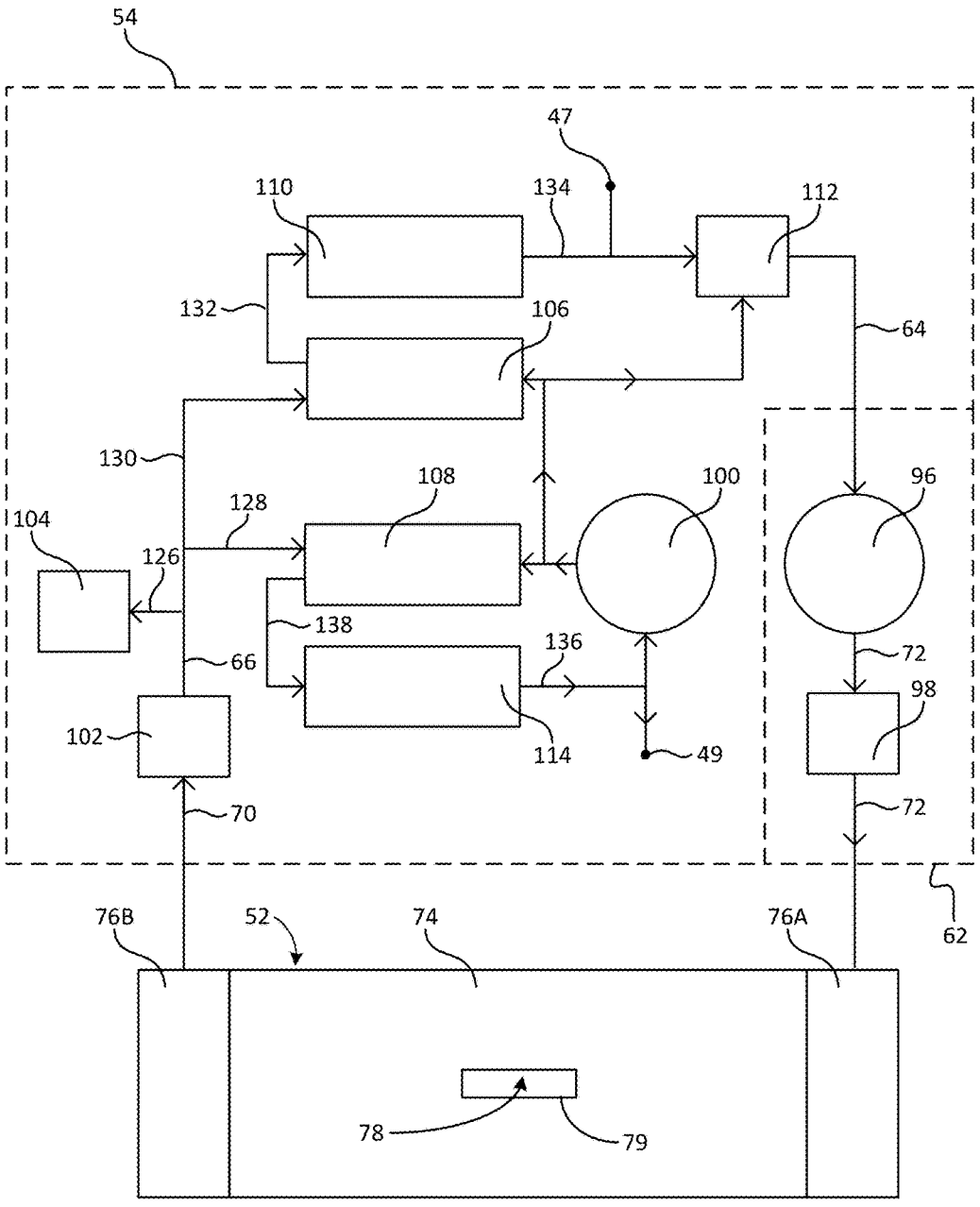
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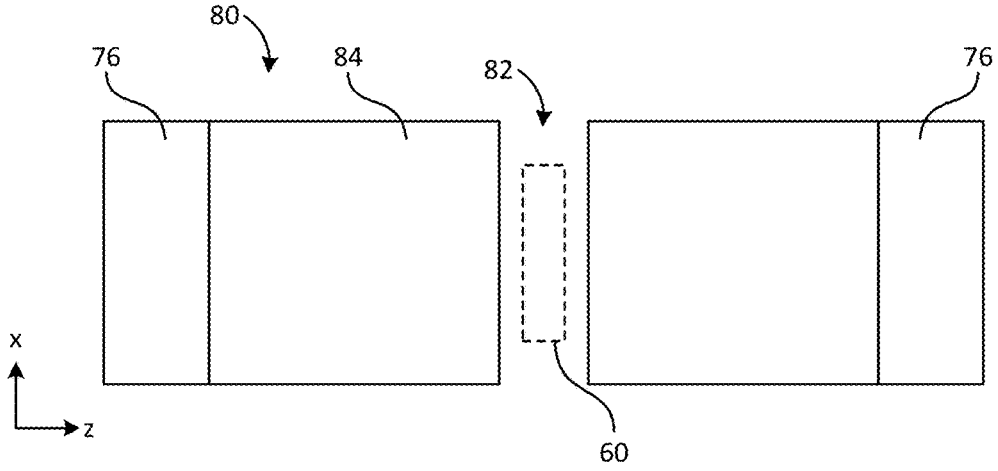
FIG. 12



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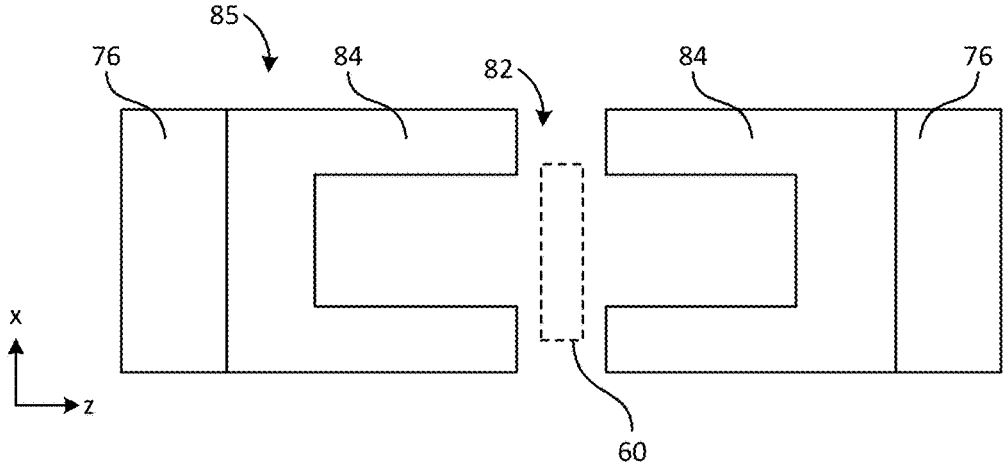

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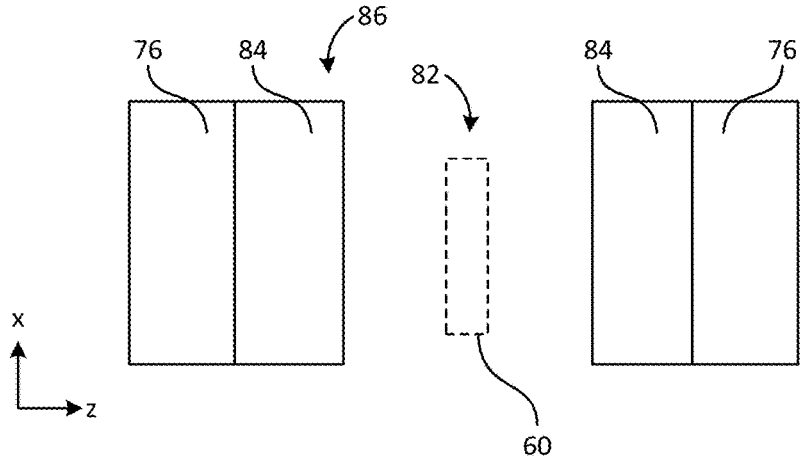

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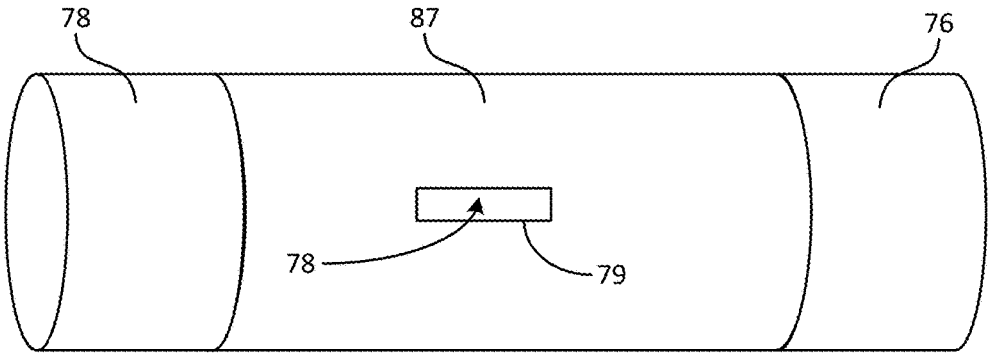

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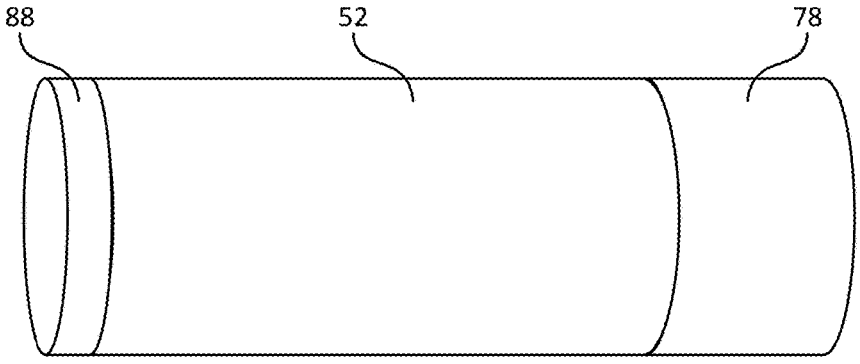

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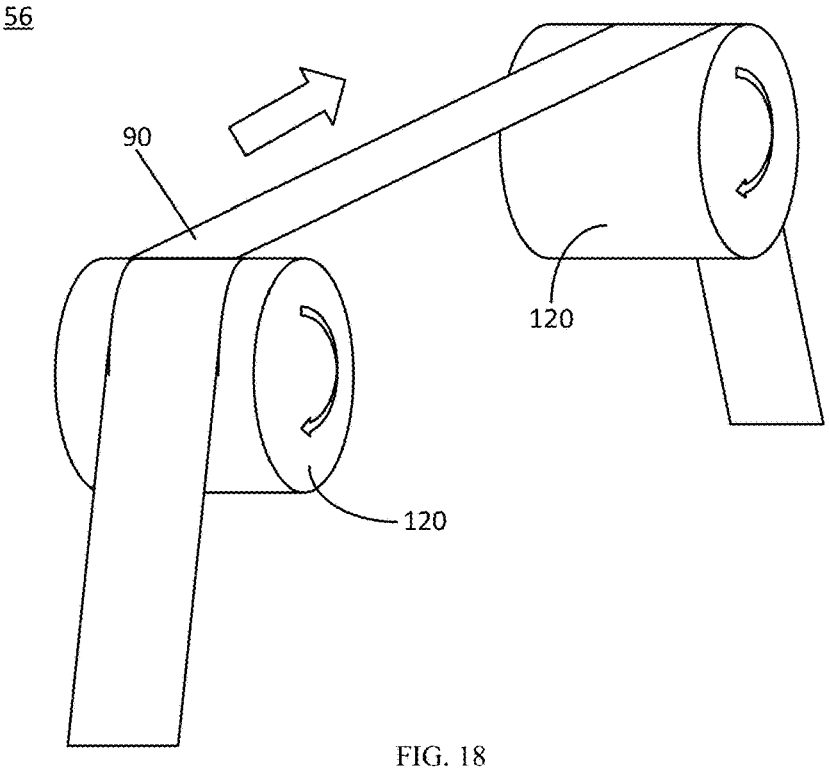

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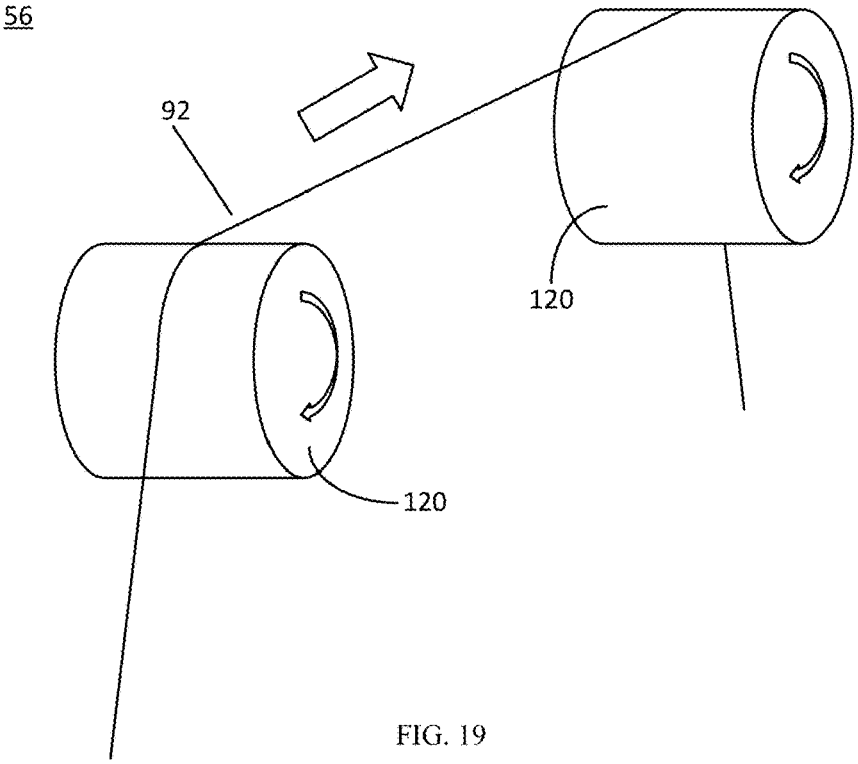

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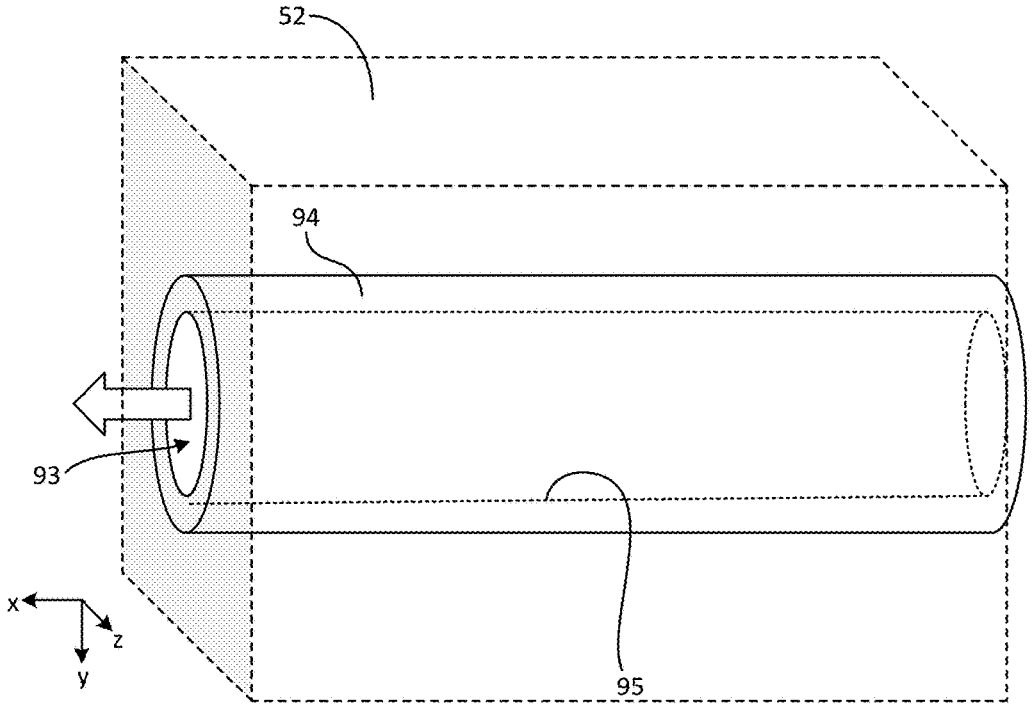

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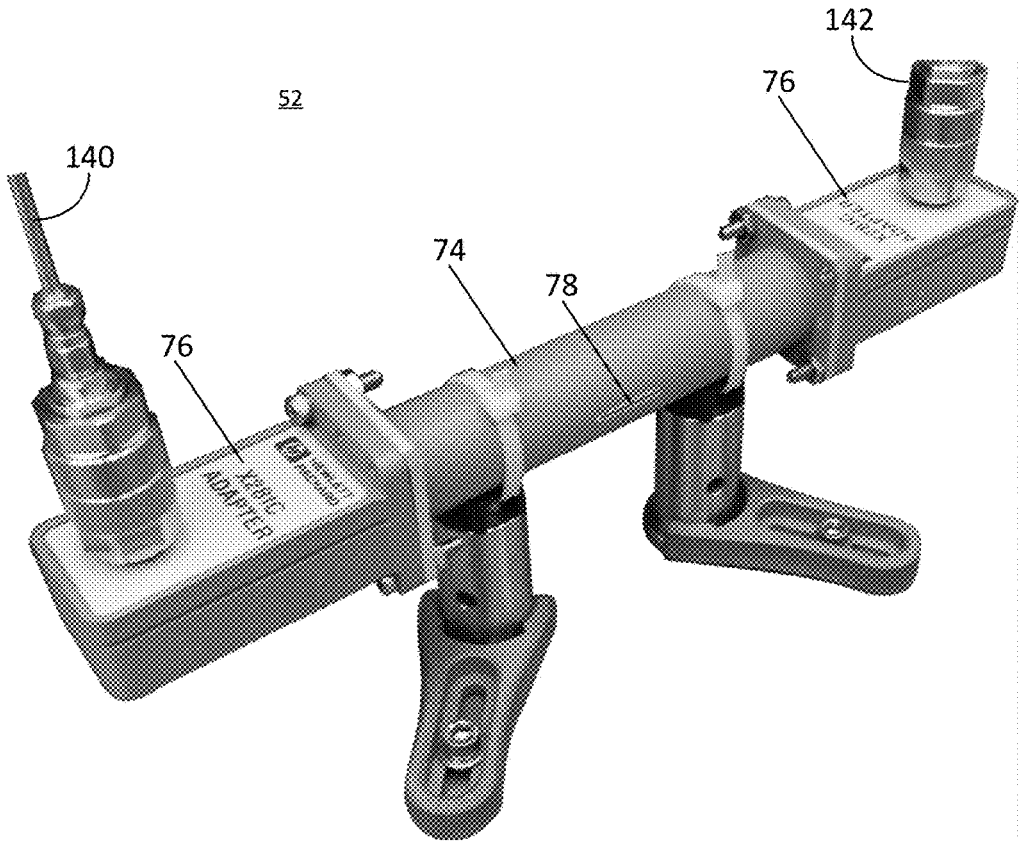

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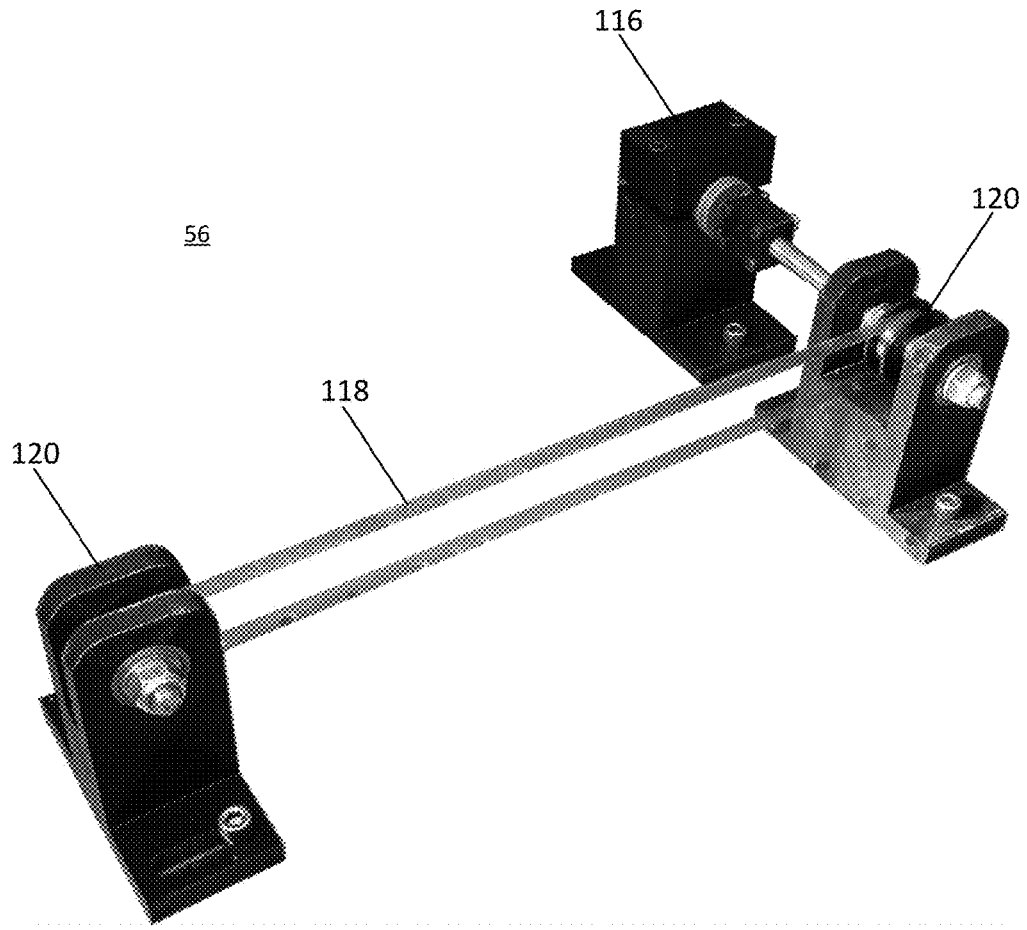

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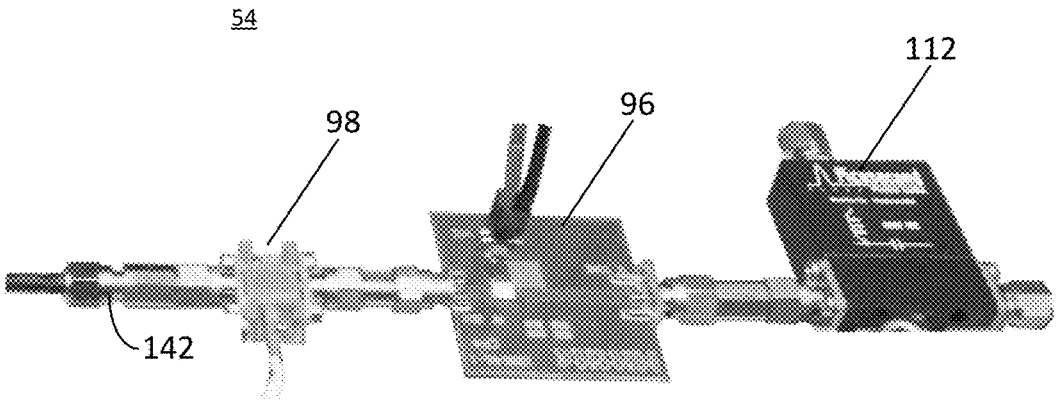

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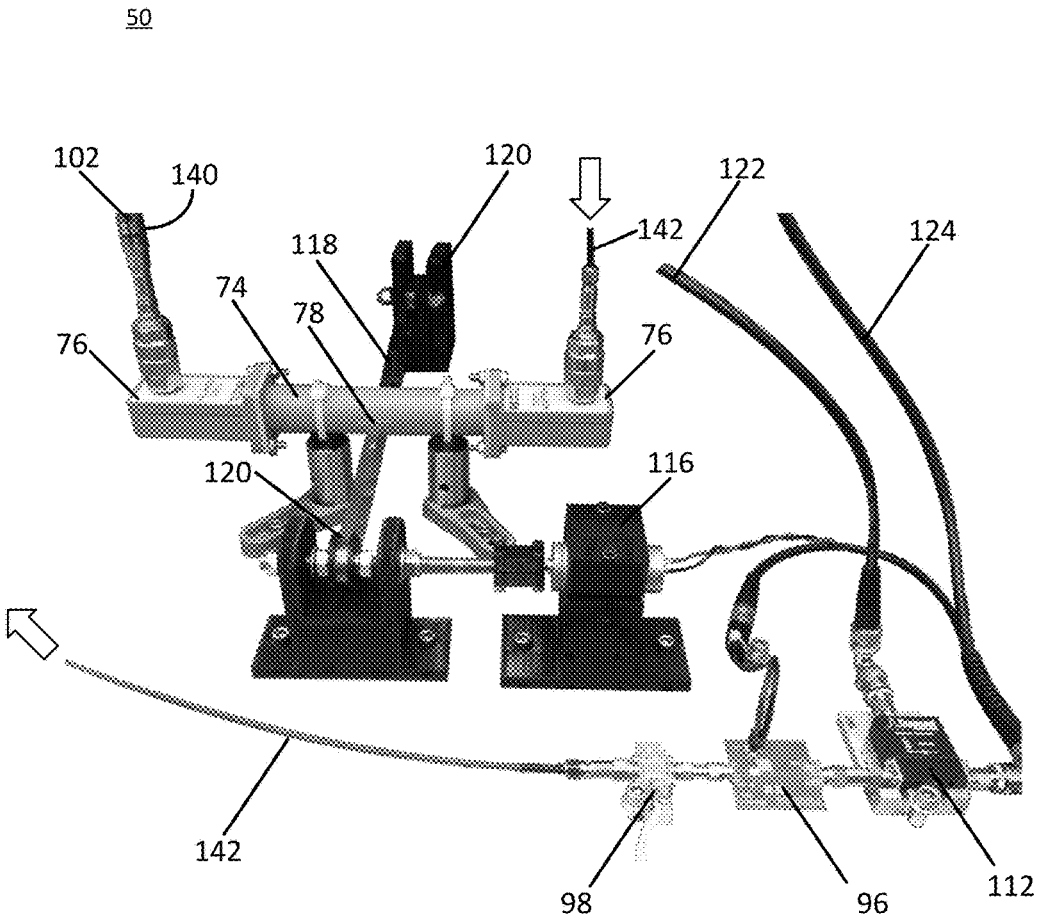

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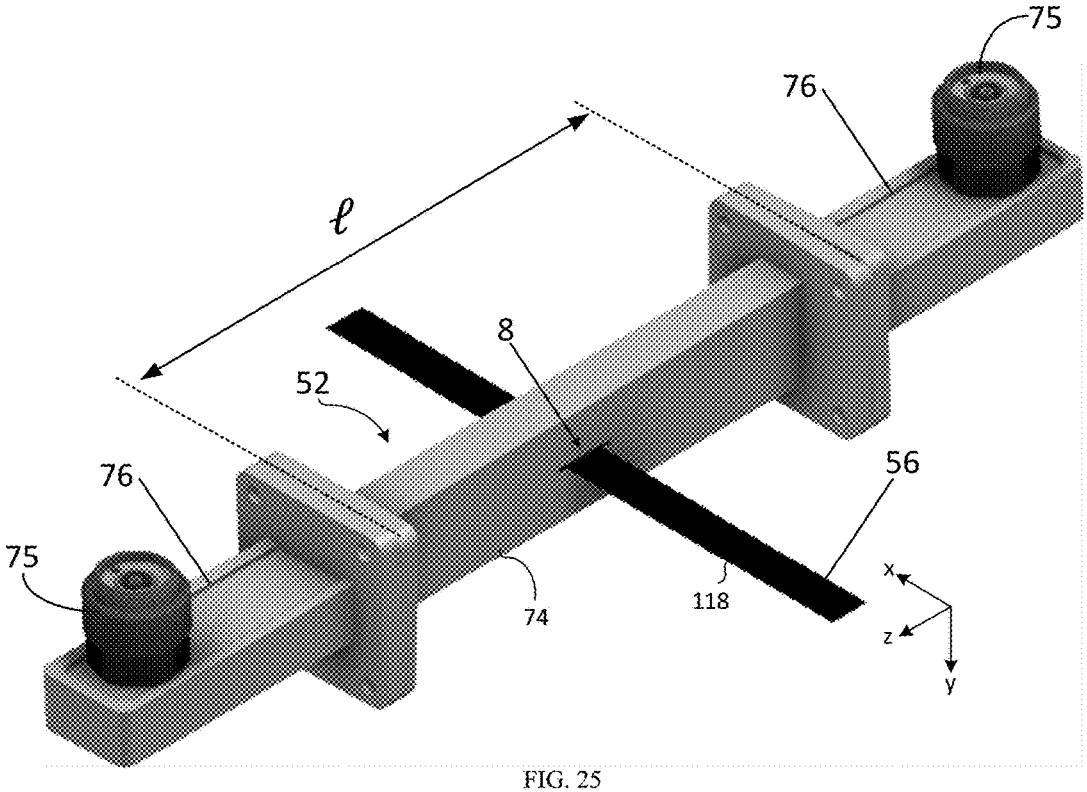

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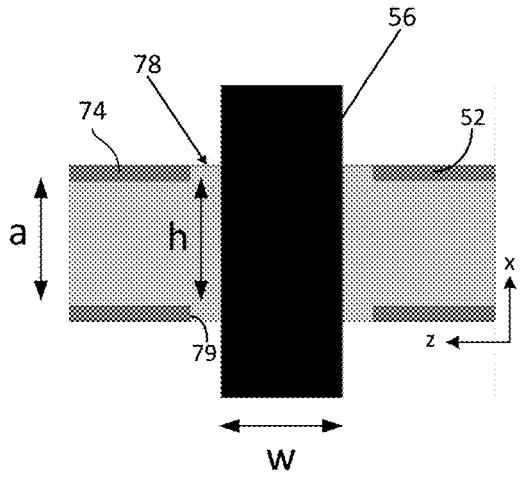

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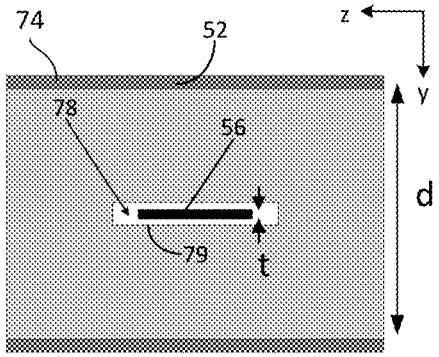
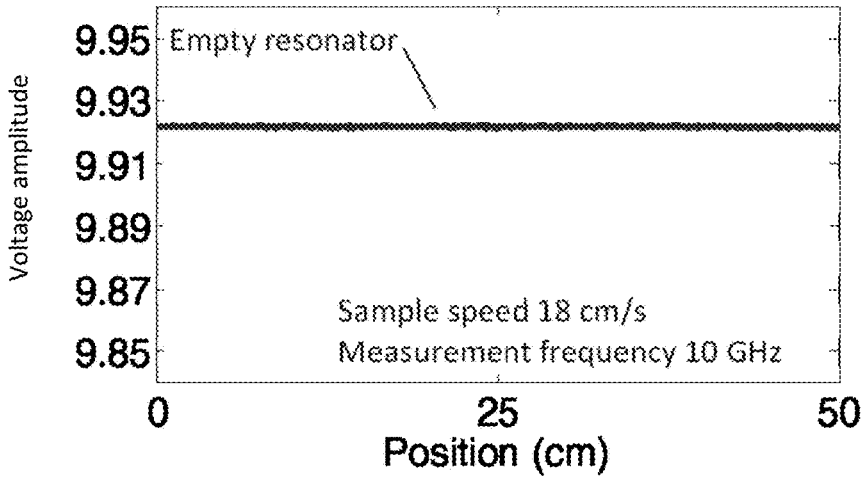


FIG. 27

FIG. 28



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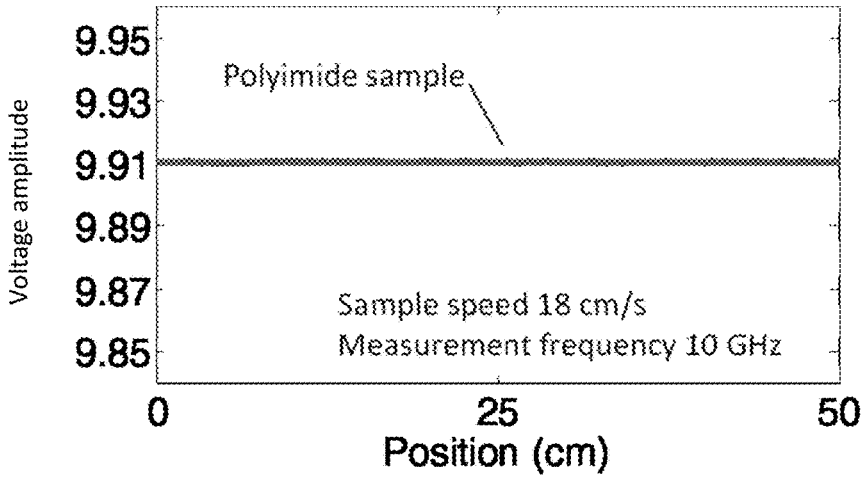

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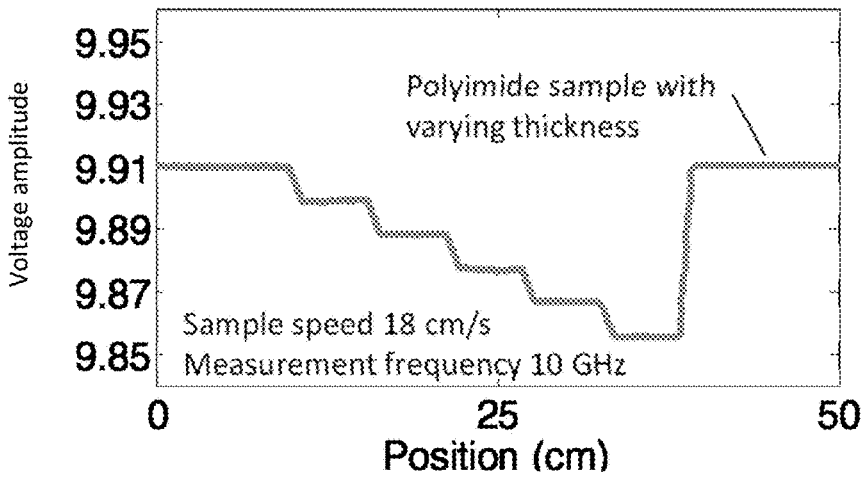

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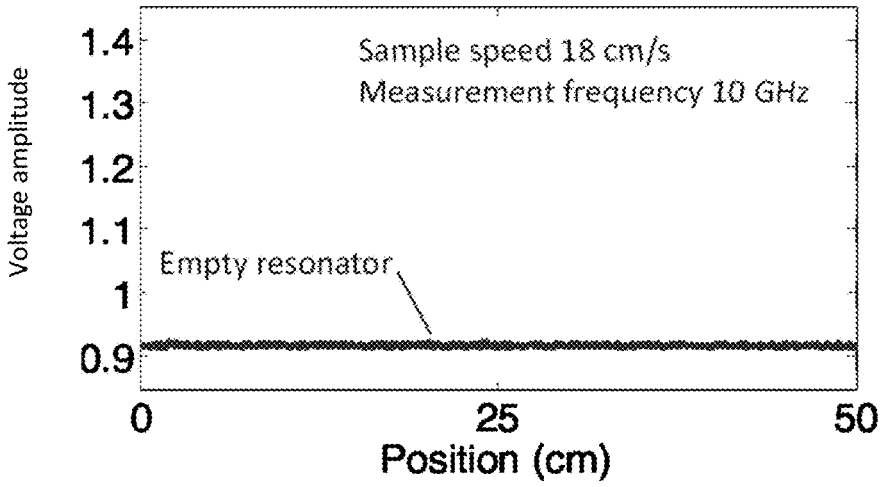

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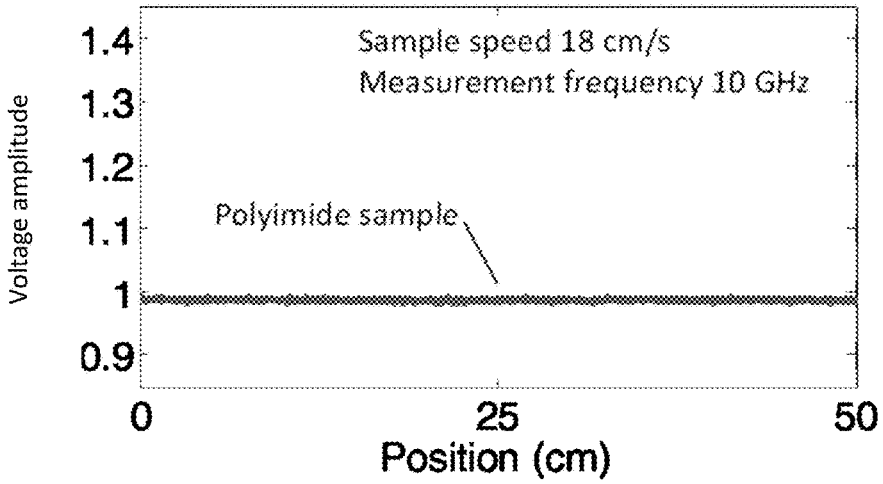

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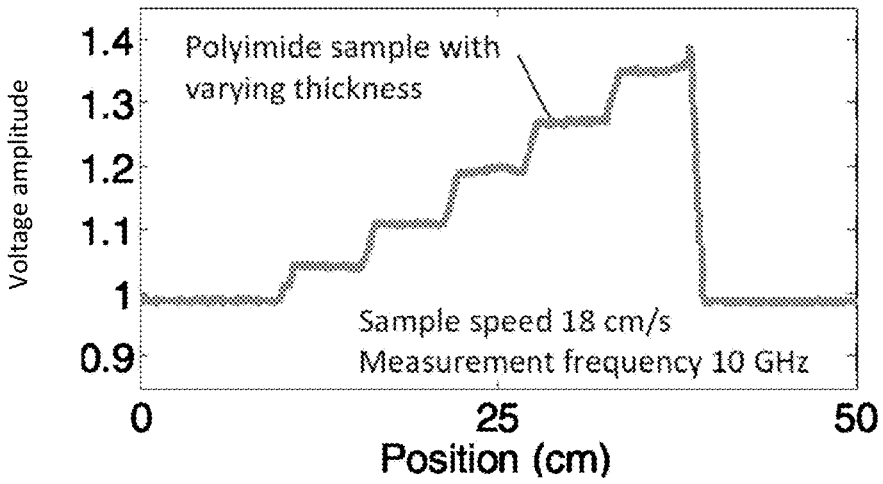


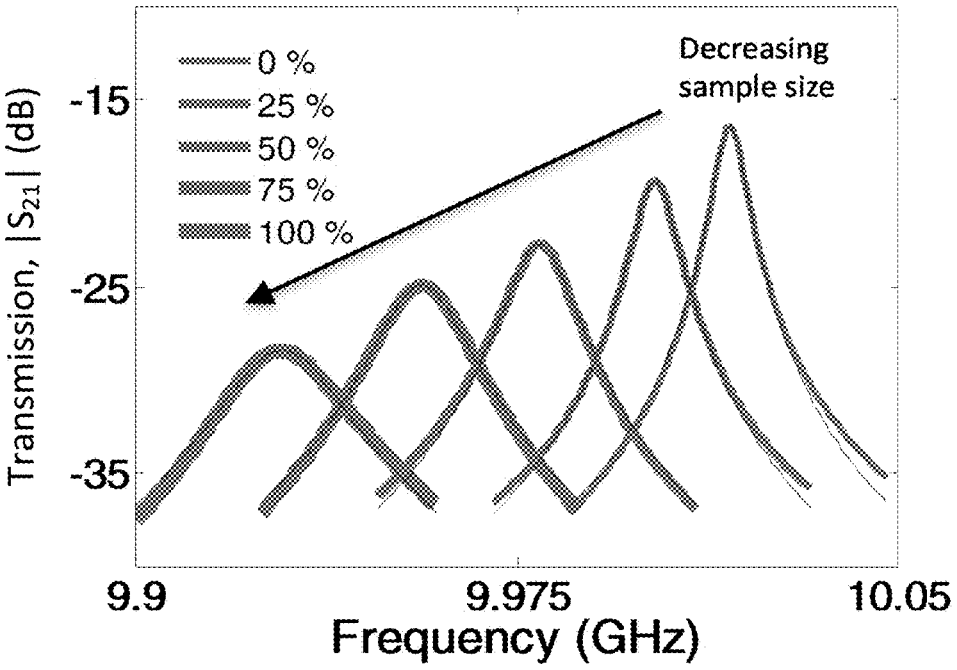

0 %
25 %
50 %
75 %
100 %
Decreasing sample size
Transmission, |S21| (dB)
-15
-25
-35
9.9
9.975
10.05
Frequency (GHz)

FIG. 34

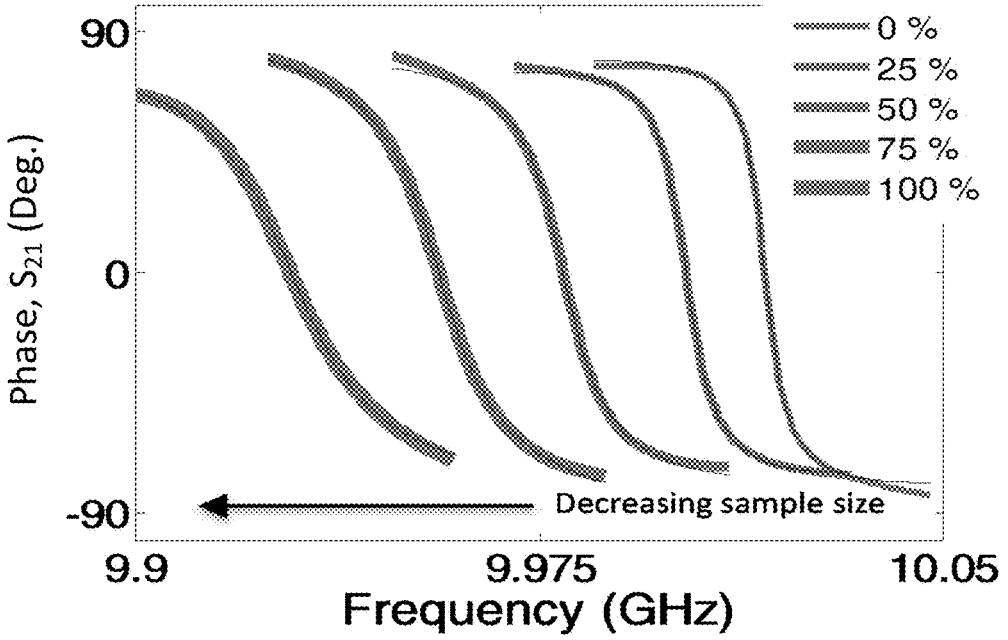

0 %
25 %
50 %
75 %
100 %
Phase, S21 (Deg.)
90
0
-90
Decreasing sample size
9.9
9.975
10.05
Frequency (GHz)

FIG. 35

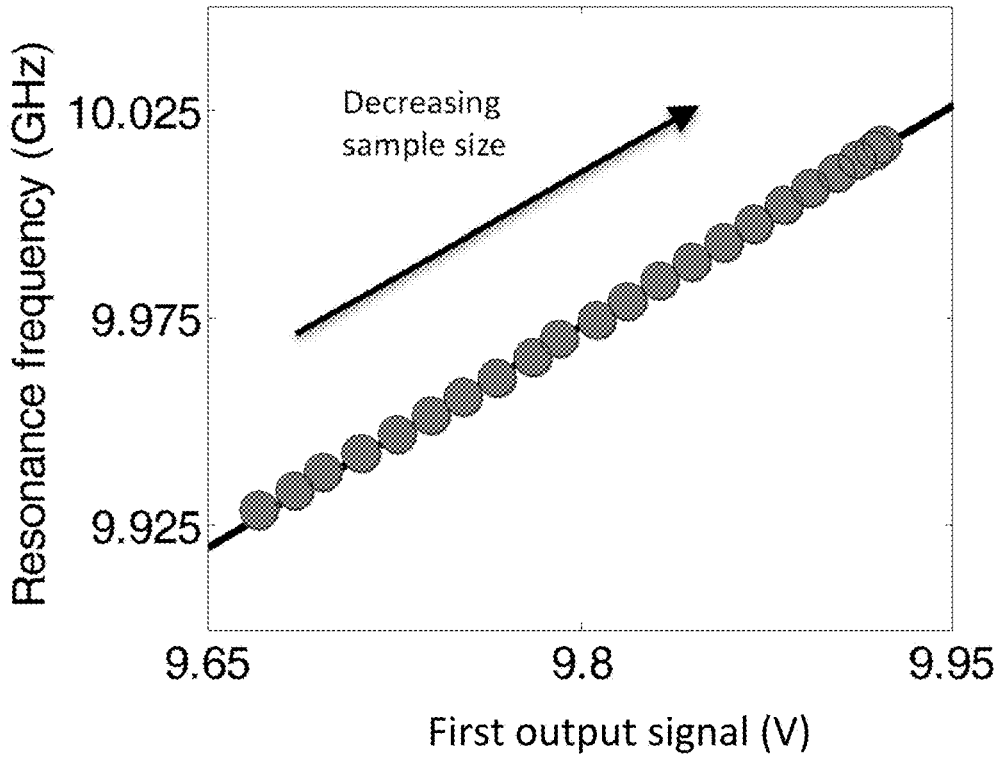

Resonance frequency (GHz)
10.025
9.975
9.925
Decreasing
sample size
9.65
9.8
9.95
First output signal (V)

FIG. 36

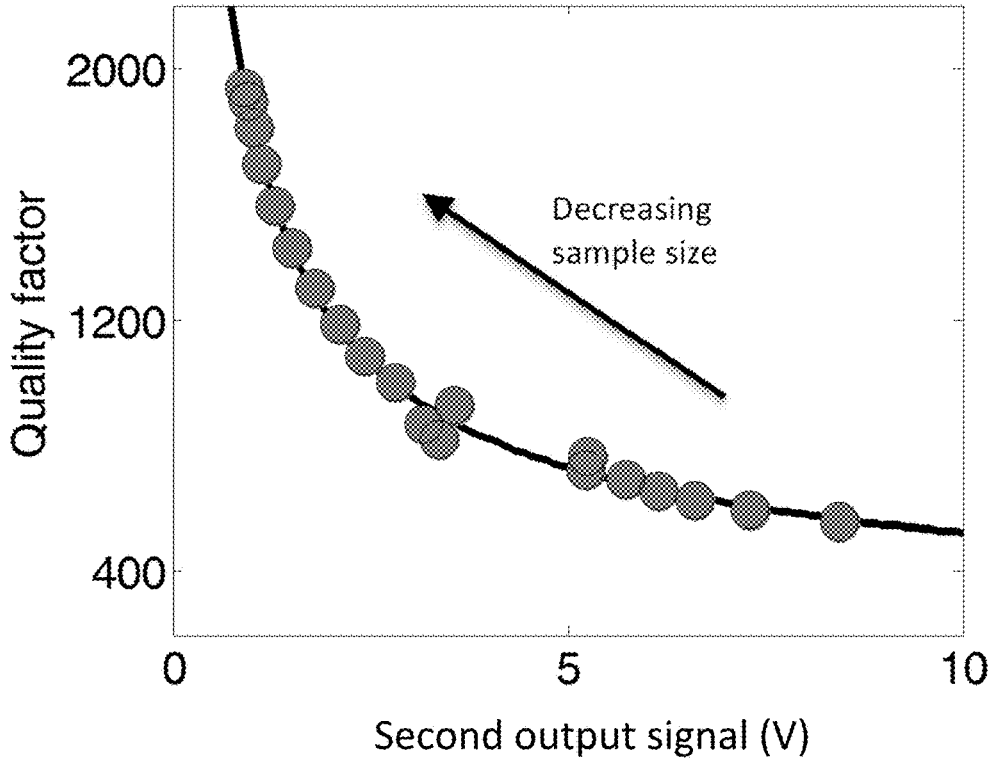

Quality factor
2000
1200
400
Decreasing
sample size
0
5
10
Second output signal (V)

FIG. 37

FIG. 38

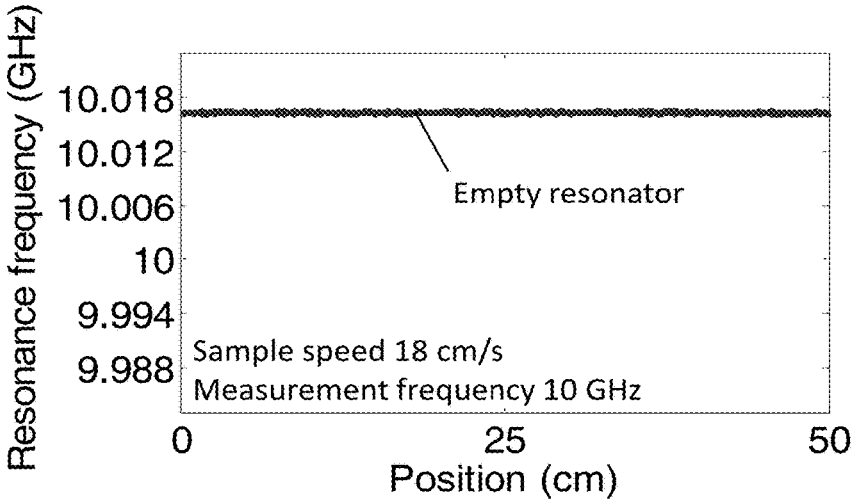
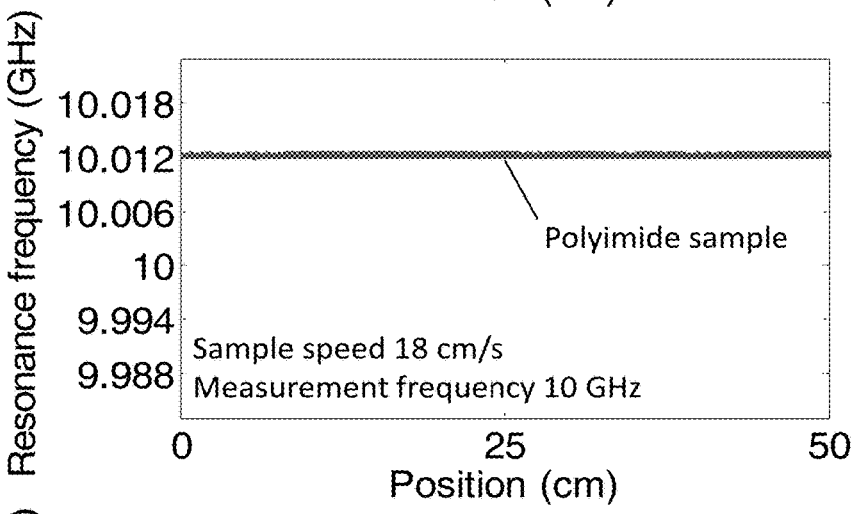


FIG. 39



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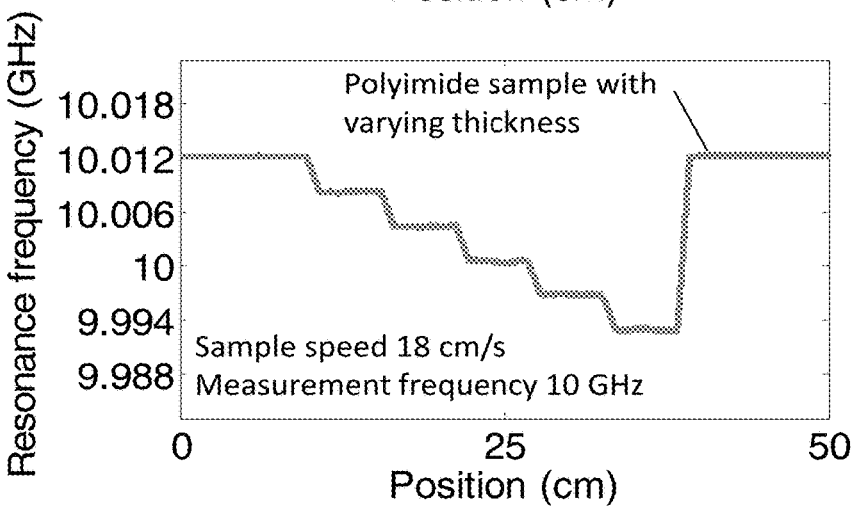

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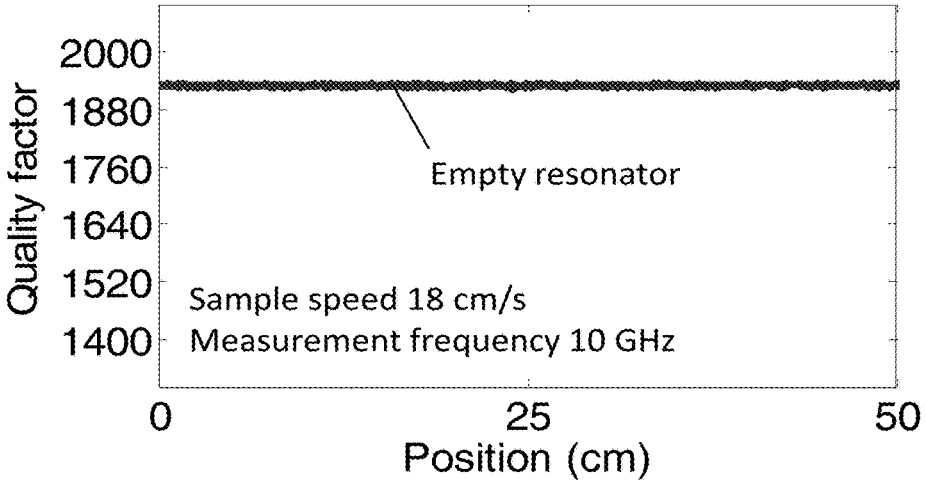


FIG. 42

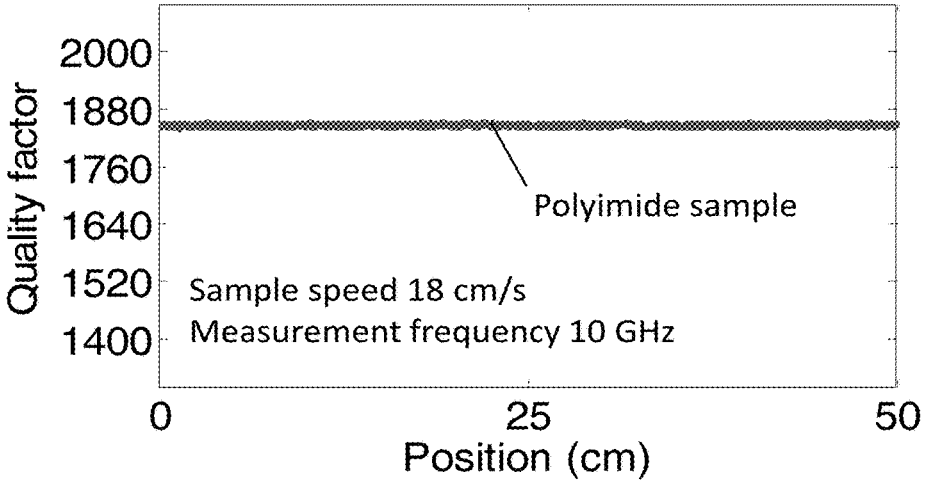
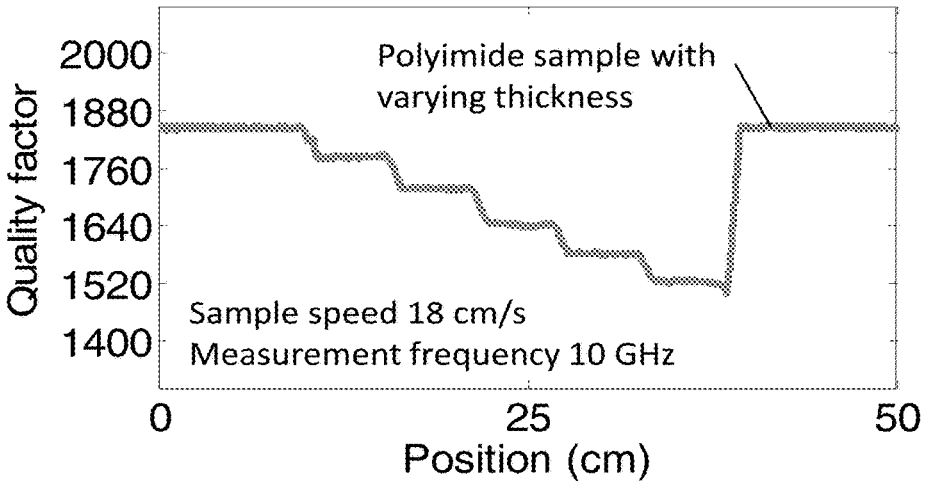


FIG. 43



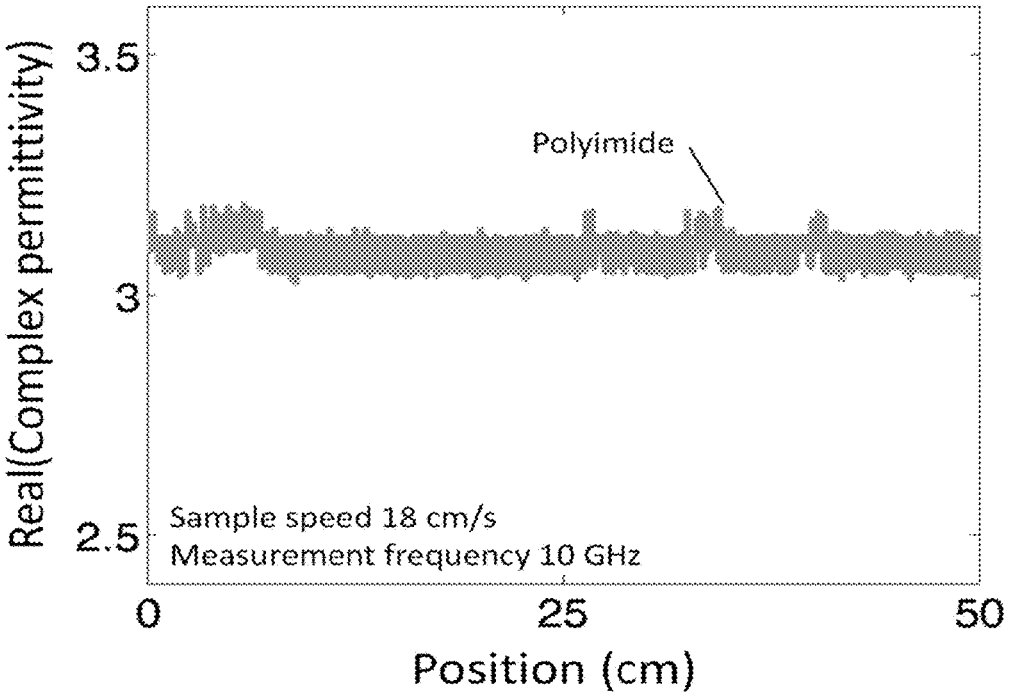

Real(Complex permittivity)
3.5
3
2.5
Polyimide
Sample speed 18 cm/s
Measurement frequency 10 GHz
0
25
50
Position (cm)

FIG. 44

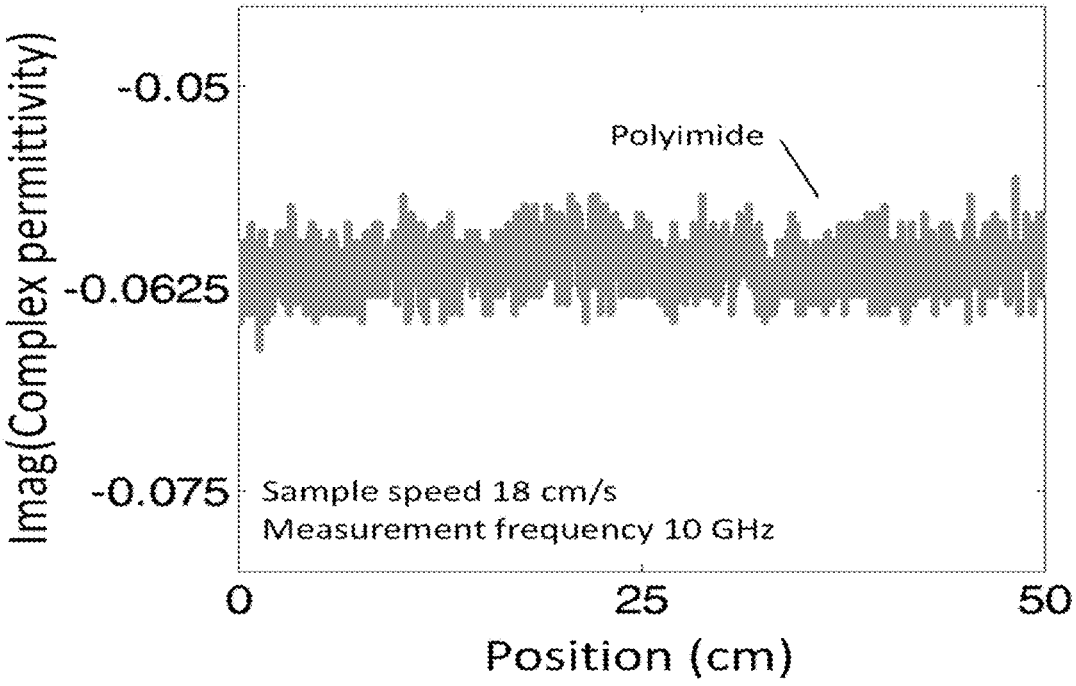

Imag(Complex permittivity)
-0.05
-0.0625
-0.075
Polyimide
Sample speed 18 cm/s
Measurement frequency 10 GHz
0
25
50
Position (cm)

FIG. 45

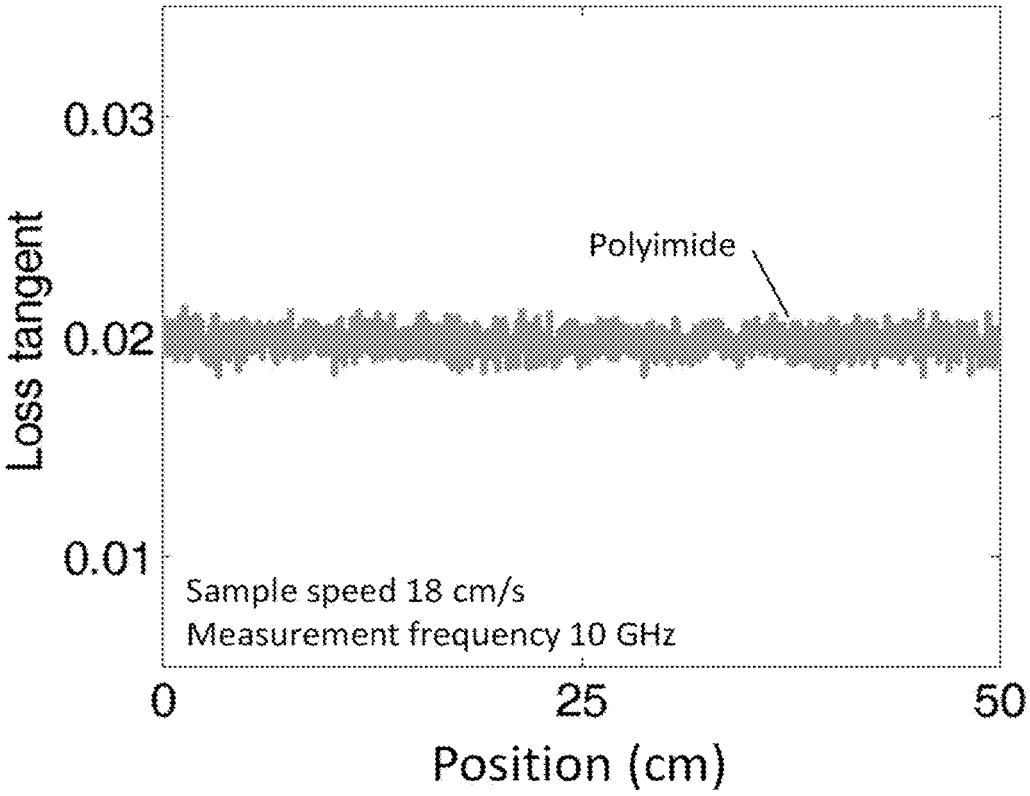

0.03
0.02
0.01
Loss tangent
Polyimide
Sample speed 18 cm/s
Measurement frequency 10 GHz
0
25
50
Position (cm)

FIG. 46

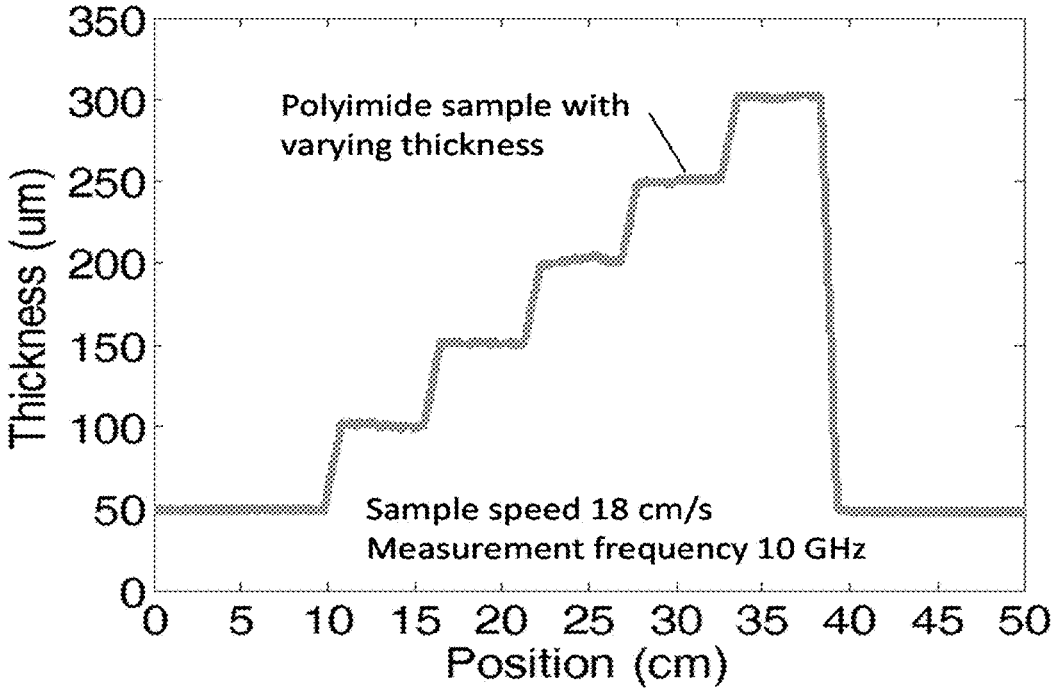

Thickness (um)
350
300
250
200
150
100
50
0
Polyimide sample with
varying thickness
Sample speed 18 cm/s
Measurement frequency 10 GHz
0 5 10 15 20 25 30 35 40 45 50
Position (cm)

FIG. 47

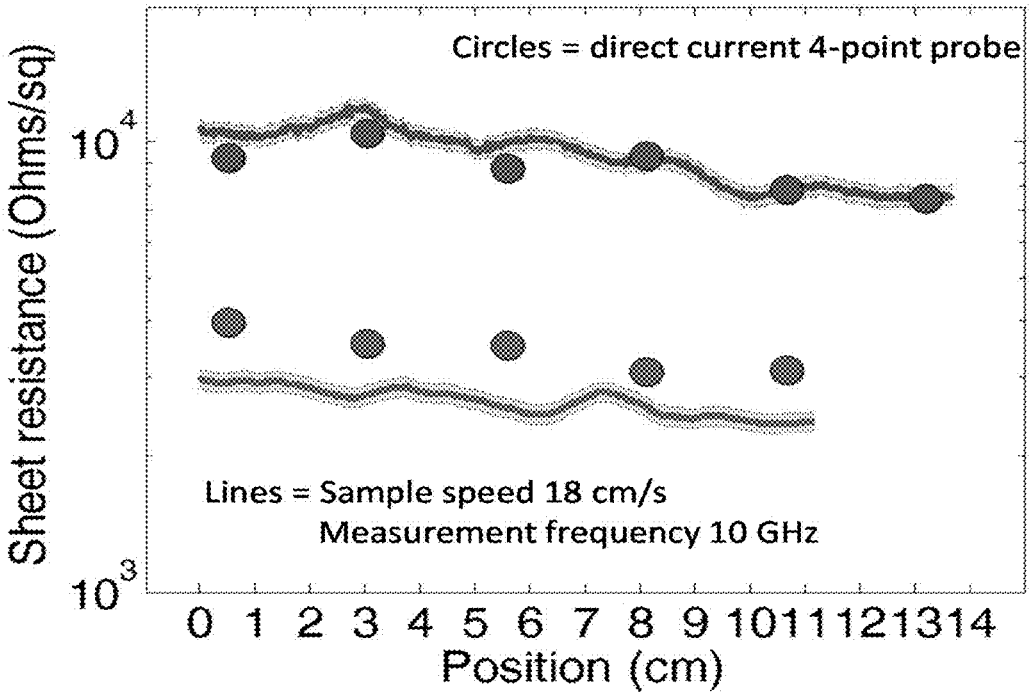

Sheet resistance (Ohms/sq)
10^4
10^3
Circles = direct current 4-point probe
Lines = Sample speed 18 cm/s
Measurement frequency 10 GHz
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Position (cm)

FIG. 48

NONCONTACT RESONAMETER, PROCESS FOR MAKING AND USE OF SAME

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application Ser. No. 62/086,748 filed Dec. 3, 2014, the disclosure of which is incorporated herein by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

This invention was made with United States Government support from the National Institute of Standards and Technology under agreement numbers 70NANB10H193 and 70NANB12H188. The Government has certain rights in the invention.

BRIEF DESCRIPTION

Disclosed is a noncontact resonameter comprising: a resonator to: produce an excitation signal comprising a field; subject a sample to the excitation signal; produce a first resonator signal in a presence of the sample and the excitation signal, the first resonator signal comprising: a first quality factor of the resonator; a first resonance frequency of the resonator; or a combination comprising at least one of the foregoing, the first resonator signal occurring in an absence of contact between the sample and the resonator; and produce a second resonator signal in a presence of the excitation signal and an absence of the sample, the second resonator signal comprising: a second quality factor of the resonator; a second resonance frequency of the resonator; or a combination comprising at least one of the foregoing; a circuit in electrical communication with the resonator to receive the first resonator signal and the second resonator signal; and a continuous feeder to: provide the sample proximate to the resonator; dispose the sample intermediately in the field of the excitation signal during production of the first resonator signal; remove the sample from the resonator; and manipulate a position of the sample relative to the resonator in a continuous motion and in an absence of contact between the sample and the resonator.

Further disclosed is a process for measuring a property of a sample, the process comprising: providing the sample to the noncontact resonameter by the continuous feeder; producing the excitation signal by the resonator; disposing the sample intermediately in the field of the excitation signal; producing the first resonator signal in a presence of the sample and the excitation signal; manipulating a position of the sample relative to the resonator in a continuous motion and in an absence of contact between the sample and the resonator; and receiving the first resonator signal by the circuit to measure the property of the sample, the property comprising an electrical property, a mechanical property, a geometric property, or a combination comprising at least one of the foregoing properties, and the property determined from the first resonator signal.

BRIEF DESCRIPTION OF THE DRAWINGS

The following descriptions should not be considered limiting in any way. With reference to the accompanying drawings, like elements are numbered alike.

FIG. **1** shows a graph of a noncontact resonameter;

FIG. **2** shows a noncontact resonameter;

FIG. **3** shows a noncontact resonameter;

FIG. **4** shows a noncontact resonameter;

FIG. **5** shows a continuous feeder proximate to a resonator;

FIG. **6** shows a continuous feeder proximate to a resonator;

FIG. **7** shows a continuous feeder proximate to a resonator;

FIG. **8** shows a side view of resonator;

FIG. **9** shows a perspective view of a continuous feeder disposed in the resonator shown in FIG. **8**;

FIG. **10** shows a top view of the continuous feeder disposed in the resonator shown in FIG. **9**;

FIG. **11** shows a circuit in electrical communication with a resonator;

FIG. **12** shows a circuit, source, and resonator in electrical communication;

FIG. **13** shows a longitudinal cross-section of a resonator;

FIG. **14** shows a longitudinal cross-section of a resonator;

FIG. **15** shows a longitudinal cross-section of a resonator;

FIG. **16** shows a longitudinal cross-section of a resonator;

FIG. **17** shows a longitudinal cross-section of a resonator;

FIG. **18** shows a continuous feeder;

FIG. **19** shows a continuous feeder;

FIG. **20** shows a continuous feeder disposed in a resonator;

FIG. **21** shows a photograph of a resonator interposed between couplers;

FIG. **22** shows a photograph of a continuous feeder;

FIG. **23** shows a photograph of a circuit;

FIG. **24** shows a photograph of an arrangement of the continuous feeder shown in FIG. **22** disposed in the resonator shown in FIG. **21** that was in electrical communication with the circuit shown in FIG. **23**;

FIG. **25** shows a continuous feeder disposed in a resonator;

FIG. **26** shows a portion of a longitudinal cross-section in an x-z plane of the resonator shown in FIG. **25**;

FIG. **27** shows a portion of a transverse cross-section in a y-z plane of the resonator shown in FIG. **25**;

FIG. **28** shows a graph of voltage versus position for an empty resonator;

FIG. **29** shows a graph of voltage versus position for a sample disposed in a resonator;

FIG. **30** shows a graph of voltage versus position for a sample disposed in a resonator;

FIG. **31** shows a graph of voltage versus position for an empty resonator;

FIG. **32** shows a graph of voltage versus position for a sample disposed in a resonator;

FIG. **33** shows a graph of voltage versus position for a sample disposed in a resonator;

FIG. **34** shows a graph of transmission versus frequency;

FIG. **35** shows a graph of phase versus frequency;

FIG. **36** shows a graph of phase versus frequency;

FIG. **37** shows a graph of phase versus frequency;

FIG. **38** shows a graph of resonance frequency versus position for an empty resonator;

FIG. **39** shows a graph of resonance frequency versus position for a sample disposed in a resonator;

FIG. **40** shows a graph of resonance frequency versus position for a sample disposed in a resonator;

FIG. **41** shows a graph of quality factor versus position for an empty resonator;

FIG. **42** shows a graph of quality factor versus position for a sample disposed in a resonator;

FIG. **43** shows a graph of quality factor versus position for a sample disposed in a resonator;

FIG. **44** shows a graph of a real part of complex permittivity versus position of a sample;

FIG. **45** shows a graph of an imaginary part of complex permittivity versus position of a sample;

FIG. **46** shows a graph of loss tangent versus position of a sample;

FIG. **47** shows a graph of sickness versus position of a sample; and

FIG. **48** shows a graph of sheet resistance versus position of a sample.

DETAILED DESCRIPTION

A detailed description of one or more embodiments is presented herein by way of exemplification and not limitation.

It has been discovered that a noncontact resonameter provides acquisition of data for a sample that is continuously fed to a resonator by a continuous feeder for determination of an electrical, mechanical, or geometric property of the sample. Further, the noncontact resonameter is configured to measure the property for the sample disposed on or part of continuous feeder that includes a web, roll, reel, wire, or capillary. A respective arrangement of the resonator and continuous feeder are selectively tailorable so that the resonator receives the sample that can have a variety of dimensions or properties. Advantageously, data for the determination of the resonance frequency and quality factor of the resonator are measured simultaneously in real time with the circuit. Without wishing to be bound by theory, it is contemplated that the resonance frequency or quality factor of the resonator relate to the property of the sample such that the property can be determined from the resonance frequency or quality factor.

In an embodiment, with reference to FIG. **1**, noncontact resonameter **50** includes continuous feeder **56** disposed proximate to resonator **52** and circuit **54** in electrical communication with resonator **52**. Here, sample **60** is provided to resonator **52** via continuous feeder **56** such that resonator **52** is configured to receive continuous feeder **56** and sample **60**. Further, resonator **56** produces excitation signal **68** and subjects sample **56** to excitation signal **68**. In this respect, sample **56** or continuous feeder **56** are disposed intermediately in the field of excitation signal **68** as depicted by excitation field **68** extending from the resonator **52**, communicating through sample **60** and continuous feeder **56**, and terminating at a location beyond sample **60**. Depending on a thickness of sample **60** or a property of sample **60** (e.g., dielectric constant or electrical permittivity), sample **60** may attenuate extension of excitation signal **68** beyond sample **60**. As used herein, being disposed "intermediately" refers to sample **60** being disposed within the field of excitation signal **68**.

According to an embodiment, resonator **52** receives the source signal **72** (not shown in FIG. **1** but see, e.g., FIG. **2**). In response to receipt of source signal **72**, resonator **52** produces excitation signal **68**. Moreover, resonator **52** produces excitation signal **68** in a presence or in an absence of sample **60** or continuous feeder **56**. Additionally, resonator **52** produces resonator signal **70** that is communicated to circuit **54**. Resonator signal **70** includes a quality factor of resonator **52**, a resonance frequency of resonator **52**, or combination thereof.

In some embodiments, resonator signal **70** is a first resonator signal produced by resonator **52** in a presence of sample **60** and excitation signal **68**, wherein the first resonator signal includes a first quality factor of resonator **52**, a first resonance frequency of resonator **52**, or a combination thereof. The first resonator signal occurs in an absence of contact between sample **60** and resonator **52** with sample **60** disposed intermediately in the field of excitation signal **68**.

In some embodiments, resonator **52** is operated in an absence of sample **60**. Here, resonator **52** produces resonator signal **70** that is a second resonator signal in a presence of excitation signal **68** and an absence of sample **60**. The second resonator signal includes a second quality factor of resonator **52**, a second resonance frequency of resonator **52**, or a combination thereof.

Circuit **54** is in electrical communication with resonator **52** and receives resonator signal **70** (e.g., the first resonator signal or the second resonator signal).

Continuous feeder **54** provides sample **60** proximate to resonator **52** and disposes sample **60** intermediately in the field of excitation signal **68** during production of the first resonator signal. Continuous feeder **54** also removes sample **60** from resonator **52** and manipulates (as indicated by a double-headed arrow interposed on continuous feeder **56** in FIG. **1**) a position of sample **60** relative to resonator **52** in a continuous motion and in an absence of contact between sample **60** and resonator **52**. It is contemplated that a distance between sample **60** and resonator **52** is controlled to position sample **60** intermediately in the field of excitation signal **68**. Control of positioning of sample **60** relative to resonator **52** is accomplished by a position of continuous feeder **56** relative to resonator **52**.

In an embodiment, as shown in FIG. **2**, noncontact resonameter **50** includes continuous feeder **56** to provide sample **60** proximate to resonator **52** and intermediately disposed in excitation signal **68** produced by resonator **52**. Source **62** provides source signal **72** (e.g., a modulated waveform) to resonator **52** that produces excitation signal **68** in response to receipt of source signal **72** from source **62**. Additionally, in response to production of excitation signal **68**, resonator **52** produces resonator signal **70** that is communicated to circuit **54** that includes primary detector **58** (e.g., a diode). Primary detector **58** produces detector signal **66** in response to receipt of resonator signal **70**. Detector signal **66** is communicated to and received by secondary detector **59** of circuit **54**.

According to an embodiment, as shown in in FIG. **3**, noncontact resonameter **50** includes continuous feeder **56** to provide sample **60** proximate to resonator **52** and intermediately disposed in excitation signal **68** produced by resonator **52**. Source **62** provides source signal **72** (e.g., a modulated waveform) to resonator **52** that produces excitation signal **68** in response to receipt of source signal **72** from source **62**. Additionally, in response to production of excitation signal **68**, resonator **52** produces resonator signal **70** that is communicated to circuit **54** that includes primary detector **58** (e.g., a diode). Primary detector **58** produces detector signal **66** in response to receipt of resonator signal **70**. Detector signal **66** is communicated to and received by secondary detector **59** of circuit **54**, wherein secondary detector **59** produces control signal **64** is communicated to and received by source **62**. It is contemplated that source signal **72** produced by source **62** includes a phase and amplitude, based on control signal **64**. Accordingly, noncontact resonameter **50** shown in FIG. **3** includes circuit **54** to provide feedback to source **62** based on detection of resonator signal **70**.

In an embodiment, as shown in FIG. **4**, continuous feeder **56** includes sample source **56** to provide sample **62** resonator

52 and to intermediately disposed sample 62 in the field of excitation 68; and sample collector 57 to collect or to remove sample 62 from resonator 52. Here, sample 62 moves in a direction from sample source 55 toward sample collector 57 and traversingly passes proximate to resonator 52 as sample 52 is intermediately disposed in the field of excitation signal 68 during communication between sample source 55 and sample collector 57.

With reference to FIG. 5 (side view of continuous feeder 56 relative to resonator 52), FIG. 6 (side view of continuous feeder 56 relative to resonator 52), and FIG. 7 (side view of continuous feeder 56 relative to resonator 52), a distance between resonator 52 and continuous feeder 56 is selectable or adjustable. In some embodiments, an adjustment of the distance between resonator 52 and continuous feeder 56 occurs during operation of noncontact resonameter 50. In a certain embodiment, the distance between resonator 52 and continuous feeder 56 is static during operation noncontact resonameter 50. According to an embodiment, as shown in FIG. 7, continuous feeder 56 is disposed in resonator 52. It should be appreciated that the first resonator signal is produced in absence of contact between resonator 52 and sample 60 or between resonator 52 and continuous feeder 56. Accordingly, sample 60 is disposed in resonator 52 with a gap (e.g., gap 82 shown in FIG. 13, FIG. 14, and FIG. 15) between sample 60 and resonator 52 such that sample 60 is intermediately disposed in the field of excitation signal 68 when first resonator signal is produced.

In an embodiment, as shown in FIG. 8 (side view of resonator 52), resonator 52 includes waveguide 74 interposed between couplers 76; and opening 78 bounded by wall 79. As shown in FIG. 9, continuous feeder 56 is communicated through opening 78 and received by resonator 52, wherein continuous feeder 56 moves in a continuous motion through resonator 72 and exits resonator 72 through opening 81. FIG. 10 shows a top view of resonator 52 with continuous feeder 56 traversing in interior of resonator 52. Here, continuous feeder 56 can provide continuously a first portion of sample 60 to resonator 52 and removes continuously a second portion of sample 60 from resonator 52. It is contemplated that the continuous motion of continuous feeder 56 is interruptible, wherein the continuous motion of continuous feeder 56 is stopped intermittently with subsequent continuation of motion of sample 60 with respect to resonator 52 so that sample 60 completely traverse resonator 52 substantially in a single dimension of travel (e.g., in a direction provided along an x-axis shown in FIG. 9) of sample 60 relative to resonator 52, from provision of sample 60 to resonator 52 to removal of sample 60 from resonator 52. Opening (78, 81) can be disposed at a selected location on resonator 52.

According to an embodiment, as shown in FIG. 11, circuit 54 is in electrical communication with resonator 52 that includes waveguide 74 and opening 78 bounded by wall 79 such that waveguide 74 is interposed between couplers (76A, 76B). Here, circuit 54 provides source signal 72 and communicates source signal 72 via signal path 83A to coupler 76A. Resonator 52 receives source signal 72 from circuit 54 via coupler 76A and produces excitation signal 68 in response to receipt of source signal 72. Waveguide 74 of resonator 52 communicates excitation signal 68 from coupler 76A to coupler 76B, and resonator signal 70 is communicated from resonator 52 via coupler 76B along signal path 83B to circuit 54. In response to receipt of resonator signal 70, circuit 54 produces first output signal 46 (not shown) and second output signal 48 that are communicated from circuit 54 respectively at first terminal 47 and second terminal 49.

With reference to FIG. 12, in an embodiment, noncontact resonameter 50 includes resonator 52 in electrical communication with circuit 54 and source 62. Circuit 54 provides feedback to source 62 to detect a change in resonance frequency or quality factor of resonator 52. Detecting the change in resonance frequency or quality factor can occur, e.g., in real time or simultaneously. The change in resonance frequency or quality factor in resonator 52 was measured as first output signal 46 (e.g., a first voltage) and second output signal 48 (e.g., a second voltage), respectively.

Resonator 52 is excited by a frequency-modulated source signal 72 produced by voltage-controlled oscillator 96. Frequency-modulated source signal 72 is amplified by amplifier 98. Frequency source 100 controls a modulation frequency of frequency-modulated source signal 72 produced by voltage controlled oscillator 96.

A first harmonic of output power from resonator signal 70 produced by resonator 52 is used to lock a center frequency of excitation signal 68 to a resonance frequency of resonator 52 by changing an amplitude of first output signal 46. A second harmonic of output power from the resonator signal 70 produced by resonator 52 is used to adjust a depth of the frequency modulation of frequency-modulated source signal 72 by tuning second output signal 48 so that a power difference between a maximum and minimum output power during a modulation cycle is constant. Second output signal 48 is monotonically related to a quality factor of resonator 52. Diode 102 receives resonator signal 70 (which, e.g., is frequency modulated) from coupler 76B and produces detector signal 66 in response to receipt of resonator signal 70. Detector signal 66 is communicated via signal paths (126, 128, 130) from diode 102. Diode 102 is an exemplary primary detector 58, and the other components in circuit 54 are included in an exemplary embodiment of secondary detector 59.

Tunable resistor 104 terminates first signal path 126, provides control of a signal-to-noise ratio, and tunes measurement speed. Second signal path 128 electrically connects diode 102 to phase sensitive detector 106 (e.g., a lock-in amplifier) that samples at the first harmonic of frequency source 100. Third signal path 130 electrically connects diode 102 to phase sensitive detector 108 (e.g., a lock-in amplifier) that samples at the second harmonic of frequency source 100.

In-phase signal 132 of phase sensitive detector 106 is communicated to and processed with controller 110 (e.g. a proportional-integrator-derivative controller) that produces first output signal 46. First output signal 46 is communicated via signal path 134 from controller 110 to first terminal 47 and bias tee 112 (e.g., a voltage adder). First output signal 46 tunes selectively a center frequency of voltage-controlled oscillator 96 of source 62. Magnitude signal 138 of phase sensitive detector 108 is communicated to and processed with controller 114 (e.g., a proportional-integrator-derivative controller) that produces second output signal 48. Second output signal 48 is communicated via signal path 136 to frequency source 100 and controls an amplitude of the frequency modulation of voltage-controlled oscillator 96 of source 62 by changing an amplitude of frequency source 100. First output signal 46 and second output signal can be measured, e.g., as voltages, at a plurality of time intervals with a voltage sensitive device such as a data acquisition board (not shown).

Exemplary circuits **54** include homodyne detection, heterodyne detection, superheterodyne detection, in-phase and quadrature mixer, and the like. It is contemplated that circuit **54** acquires scattering parameter based on resonator signal **70** to determine the resonance frequency or quality factor of resonator **52** in real time. Moreover, acquisition of resonator signal **70** can occur whether or not sample **60** or continuous feeder **52** is disposed in resonator **52**. It is contemplated that resonator signal **70** can be calibrated in an absence of sample **60** or continuous feeder **52** disposed in resonator **52**. In a certain embodiment, resonator signal **70** is calibrated in a presence of a sample **60** or continuous feeder **52** having a known value of an electrical property, a mechanical property, a geometric property, or combination thereof. That is, circuit **54** include diode **102** in electrical communication with resonator **52** to receive, from resonator **52**, the first resonator signal and the second resonator signal, wherein diode **102** produces detector signal **66** in response to receipt of the first resonator signal or the second resonator signal.

Source **62** includes a voltage-controlled oscillator **96** to produce source signal **72**. The frequency of the source signal **72** is effective to excite resonator **52** such that resonator **52** produces excitation signal **68**. In this manner, a standing wave can form, e.g., in a waveguide **74** or in free-space for a free space cavity of resonator **52** from excitation signal **68** generated by resonator **52** in response to provision of source signal **72** (having an amplitude and phase based on control signal **64**). As such, source signal **72** can have a frequency, phase, amplitude, or combination thereof selected to excite resonator **52** to produce an excitation signal **68** can have electromagnetic field, acoustic field, or a combination thereof.

Resonator **52** includes a free space resonator or a cavity resonator. Further, resonator **52** can include an electromagnetic resonator, a mechanical resonator, or a combination thereof. Exemplary electromagnetic resonators include microwave resonators and the like. Exemplary mechanical resonators include acoustic resonators and the like. In an embodiment, resonator **52** is the cavity resonator, and the cavity resonator includes wall **79** bounding a sample space to receive sample **60**; and opening **78** to transmit sample **60** to the sample space, wherein sample **60** does not contact resonator **52**. In a particular embodiment, resonator **52** is the free-space resonator, and the free-space resonator includes a sample space to receive sample **60** spaced apart from resonator **52**.

With reference to FIG. **13** (longitudinal cross-section of an embodiment of resonator **52**), FIG. **14** (longitudinal cross-section of an embodiment of resonator **52**), FIG. **15** (longitudinal cross-section of an embodiment of resonator **52**), FIG. **16** (perspective view of an embodiment of resonator **52**), and FIG. **17** (perspective view of an embodiment of resonator **52**), exemplary resonators respectively include dielectric resonator **80** (also referred to as a split-post resonator) (FIG. **13**), split-cylinder resonator **85** (FIG. **14**), split capacitor resonator **86** (FIG. **15**), cylindrical cavity resonator **87** (FIG. **16**), and resonator with aperture **88** (FIG. **17**). In an embodiment, resonator **52** includes pole **84** interposed between couplers **6** and separated by gap **82** for disposition and receipt of sample **60** or continuous feeder **56** between poles **84**. Accordingly, sample **60** or continuous feeder **56** is disposed in resonator **52** and changes the resonance frequency or quality factor of resonator **52**. Similarly, proximity of sample **62** aperture **88** of resonator **52** shown in FIG. **17** changes of resonance frequency or quality factor of resonator **52**.

A size, shape, or type (e.g., electromagnetic or acoustic) of resonator **52** can be effective to produce excitation signal **68** in response to receipt of source signal **72**. Further, the size or shape of resonator **52** can be selected to interact with sample **60** to produce resonator signal **70** that includes first resonator signal from presence of sample **60** intermediately disposed in the field of excitation signal **68**. In an embodiment, resonator **52** includes a microwave resonator in which sample **60** is disposed and subjected to excitation signal **68** that includes a microwave frequency. Here, resonant signal **70** (e.g., first resonant signal) produced from interaction of excitation signal **68** with the sample **60** includes a resonant frequency or quality factor of resonator **52**. In a particular embodiment, resonator **52** includes a pair of acoustic resonators opposing each other and in which sample **60** is interposed between the acoustic resonators such that excitation signal **68** is produced from receipt of source signal **72**. Here, sample **60** is intermediately disposed in the acoustic field of excitation signal **68** such that resonant signal **70** (e.g., first resonant signal) produced from interaction of acoustic excitation signal **68** with sample **60** includes a resonant frequency or quality factor of resonator **52**.

Continuous feeder **56** provides sample **60** to resonator **52** and dispose sample **60** intermediately in the field of excitation signal **68** during production of the first resonator signal. Additionally, continuous feeder **56** removes sample **60** from resonator **52** and manipulates a position of sample **60** relative to resonator **52** in a continuous motion and in an absence of contact between sample and resonator **52**. In an embodiment, continuous feeder **56** moves sample **60** in one direction relative to resonator **52**. In some embodiments, continuous feeder **56** moves sample **60** back and forth relative to resonator **52**.

According to an embodiment, continuous feeder **56** includes a flexible or rigid material that translates sample **60** relative to resonator **52**. Continuous feeder **56** can include rollers **120** to translate web **90**, a belt, roll, and the like to position sample **60**, as shown in FIG. **18**. In some embodiments, continuous feeder **56** include of wire **92**, a tube, cord, filament, fiber, and the like that moves sample **60** relative to resonator **52** as shown in FIG. **19**. In some embodiments, as shown in FIG. **20**, continuous feeder **56** includes capillary **94** disposed in resonator **52** and stationary relative to resonator **52** such that sample **60** is communicated through capillary **94** and traverses resonator **52** during passage through capillary **94**. According to an embodiment, capillary **94** moves relative to resonator **52** and communicates sample **60** in an intermediate part of the field of excitation signal **68** produced by resonator **52**. Here, capillary **94** includes flow path **93** bounded by wall **95**. Wall **95** of capillary **94** can be isolated from resonator **52** so that capillary **94** and is not contact resonator **52**. In some embodiments, capillary **94** and being contact with resonator **52** with sample **60** being subjected to excitation signal **68** in an absence of contact between sample **60** in resonator **50**.

Continuous feeder provides the sample to the resonator at a feed rate effective for resonator **52** to produce resonator signal **70** from interaction of excitation signal **68**. The feed rate can be from 1 micrometer per second (μm/s) to several kilometers per second (km/s), specifically from 1 mm/s to 10 km/s, more specifically from 1 cm/s to 1 km/s, and further specifically from 10 cm/s to 100 cm/s. In an embodiment, the feed rate is greater than or equal to 10 cm/s. The feed rate can be dynamic and varied from a first feed rate to a second rate, increased, decreased, or a combination thereof in a selected sequence or combination.

According to an embodiment, the continuous motion is interruptible such that continual motion of sample **60** provided by continuous feeder **56** can be stopped and then motion resumed. Moreover, continuous motion **56** occurs substantially in a single dimension of travel of sample **60** relative to resonator **52**, from provision of sample **60** to resonator **52** to removal of sample **60** from resonator **52**.

In an embodiment, sample **60** includes a solid, liquid, gas, or a combination thereof. Further, sample **60** can be a composition that includes a single substance or a combination of substances. Sample **60** can be composition that is homogeneous or heterogeneous. Further, sample **60** can include a gradient in a concentration of a species (e.g., an atom, molecule, complex, and the like) or a property (e.g., a gradient in dielectric constant) across a length of sample **60** provided to resonator **60**. In a particular embodiment, sample **60** is a solid that includes a weave, laminate, and the like. In an embodiment, sample **60** includes the solid or liquid and a gaseous vapor of the solid or liquid. In a certain embodiment, sample **60** includes a particle disposed in a fluid, wherein sample **60** is communicated through continuous feeder and traverses resonator **52** during which time sample **60** is intermediately disposed in the field of excitation signal **68** produced by resonator **52**. According to an embodiment, sample **60** is an integrated component of continuous feeder **56** provided to resonator **52**, e.g., continuous feeder **56** can include web **118**, wherein web **118** is a solid material that is sample **60**, e.g., a polymer film. In some embodiments, sample **60** is disposed on, disposed in, transported by, or conveyed with continuous feeder **56** to be communicated to and provided to resonator **52**. Here, continuous feeder **56** can include a substrate such as web **118** or capillary **94**, wherein sample **60** can be a solid or liquid disposed on web **118**, or a solid, liquid, or gas, that is disposed in capillary **94**.

As sample **60** is communicated by continuous feeder **56** and passes intermediately through the field of excitation signal **68** produced by resonator **52**, sample **60** interacts with excitation signal **68** and can change a resonant frequency or quality factor of resonator **52**. Such changes are communicated as resonator signal **70** to circuit **54** from resonator **52**. In this manner, noncontact resonameter **50** provides a measurement of a property of sample **60**. The property includes an electrical property, a mechanical property, a geometric property (e.g., a shape, volume, thickness, dimension such a length, and the like), or a combination comprising at least one of the foregoing properties, wherein the property is determined from the first resonator signal. According to an embodiment, the property is the electrical property, and the electrical property includes a permittivity, a dielectric constant, an electrical conductivity, a permeability, or a combination thereof.

In an embodiment, with reference to FIG. **21**, which shows a photograph of resonator **52**, resonator **52** includes waveguide **74** interposed between couplers **76**. Coupler **76** includes a microwave coaxial connector to waveguide adapter. Waveguide **74** includes a rectangular waveguide, wherein coupler **76** is cross-polarized with respect to an electric field in waveguide **74**. Moreover, waveguide **74** includes opening **78** for receipt of continuous feeder **56**.

Further, with reference FIG. **22**, which shows a photograph of continuous feeder **56**, continuous feeder **56** includes rollers **120** mounted on holders, wherein web **118** is looped around rollers **120**. Motor **116** rotates rollers **116** to provide motion to continuous feeder **56** in a selectively controlled manner. Web **118** is disposed in resonator **52**. When motor **116** turns rollers **120**, web **118** is continuously fed through resonator **52**. Additionally, sample **60** can be a discrete sample or continuous sample and disposed on web **118** to be communicated through resonator **52**. In an embodiment, sample **60** is part of continuous feeder **56** (e.g., web **118**). In an embodiment, sample **60** is disposed on continuous feeder **56**.

Circuit **54** receives resonant signal **70** from resonator **52** and produces control signal **64** that is communicated to source **62**. FIG. **23** shows a photograph of a portion of circuit **54** and source **62** that includes bias tee **112**, voltage controlled oscillator **100**, and amplifier **98**.

With reference FIG. **24**, which shows a photograph of noncontact resonameter **50** (with some electrical connections shown), noncontact resonameter **50** includes resonator **52**, continuous feeder **56**, and circuit **54**. Here, resonator **52** is as shown in FIG. **21**. Web **118** was routed through opening **78** of resonator **52** to provide a closed loop of web **118** around rollers **120** of continuous feeder **56**. Motor **116** rotates rollers **120** and moves web **118**. Circuit **54** (also shown in FIG. **23**) connects to resonator **52** with voltage controlled oscillator **96** connected to amplifier **98** to produce source signal **72** that is communicated to resonator **52** to excite a cavity of resonator by production of excitation signal **68**. Diode **102** rectifies frequency-modulated resonator signal **70** produced by resonator **52**. A plurality of phase sensitive detectors (e.g., lock-in amplifiers) and integrated proportional-integrator-derivative controllers process detector signal **66** from diode **102** to produce first output signal **46** (e.g., a voltage) and second output signal **48** (e.g., a voltage). First output signal **46** is communicated to low frequency input of bias tee **112** via coaxial cable **122**, and second output signal **48** is communicated to high frequency input of bias tee **112** via coaxial cable **124**.

According to an embodiment, noncontact resonameter **50** includes resonator **52** to receive sample **60** and continuous feeder **56**; continuous feeder **56** to provide sample **60** to resonator **52**; and circuit **54** to measure the resonance frequency or quality factor of resonator **52**. Resonator **52** can be detachably disposed on continuous feeder **56**; continuous feeder **56** can be detachably disposed on a housing of circuit **56**; or a combination thereof.

Noncontact resonameter **50** has beneficial and advantageous uses. In an embodiment, a process for measuring a property of sample **60** includes providing sample **60** to noncontact resonameter **52** by continuous feeder **56**; producing excitation signal **68** by resonator **52**; disposing sample **60** intermediately in the field of excitation signal **68**; producing the first resonator signal in a presence of sample **60** and excitation signal **68**; manipulating a position of sample **60** relative to resonator **52** in a continuous motion and in an absence of contact between sample **60** and resonator **52**; and receiving the first resonator signal by circuit **54** to measure the property of sample **60**. The property includes the electrical property, mechanical property, geometric property, or a combination thereof, wherein the property is determined from the first resonator signal. The property can be determined from the first resonator signal in a number of ways such as those described in the Examples provided herein.

In an embodiment, the process further includes producing the second resonator signal in a presence of excitation signal **68** and an absence of sample **60**. According to an embodiment, the process includes providing source signal **72** to resonator **52** to control producing excitation signal **68** by resonator **52**; and producing control signal **64** by circuit **54** to control a phase and amplitude of source signal **72**.

According to an embodiment, excitation signal **68** includes an electromagnetic resonance created by resonator **52**, e.g., a microwave resonance, and resonator **52** independently includes a quality factor with respect to energy storage of the electromagnetic resonance. In an embodiment, excitation signal **68** includes an acoustic resonance created by resonator **52**, and resonator **52** independently includes a quality factor with respect to energy storage of the acoustic resonance.

In an embodiment, resonator **52** includes a fastener to detachably dispose continuous feed **52** to resonator **52**; opening **78** (or a feed-through) in resonator **52** to receive continuous feeder **56** and sample **60**; and a gap in resonator **52** to detachably dispose continuous feeder **56**. In an embodiment, continuous feeder **56** includes web **118**; roller **120**; a reel; a wire; or a capillary to move sample **60** such as the liquid, gas, solid, or a combination thereof. According to an embodiment, resonator **52** includes: waveguide **74** that includes opening **78** to receive continuous feeder **56**; dielectric resonator **80** that includes gap **82** interposed between dielectric plates detachably mounted onto continuous feeder **56**; an inductor in electrical communication with a capacitor that has an opening or feed-through to receive continuous feeder **56**, wherein aperture **88** can be detachably mounted onto continuous feeder **56**; or a combination thereof. In an embodiment, noncontact resonameter **50** further includes continuous feeder **56**, wherein continuous feeder **56** is interposed between the fastener and resonator **52** such that sample **60** can be continuously communicated and disposed in or adjacent to resonator **52**.

In an embodiment, resonator **70** includes electrical contributions from continuous feeder **56** and sample **60**, wherein an electrical contribution from continuous feeder **56** is removed from an electrical contribution of sample **60** in resonator signal **70**. In an embodiment, circuit **54** is configured to measure the resonance frequency or quality factor of resonator **52**, wherein circuit **54** can include an in-phase and quadrature mixer, a scattering parameter measurement, voltage-controlled oscillator with a feedback circuit (the feedback circuit can include a proportional-integrator-derivative signal processor, a diode, a lock-in amplifier, a bias tee, an amplifier, filter, or a combination thereof). In an embodiment, resonator **52** is configured such that the resonance frequency or quality factor of resonator **52** is changed by presence of sample **60** or continuous feeder **56**. In an embodiment, circuit **54** is configured to measure the change in the resonance frequency and quality factor of resonator **52**. In an embodiment, the property of sample **60** (e.g., the dielectric constant, electrical conductivity, and the like) with a known geometry is determined from the change in the resonance frequency or quality factor due to presence of sample **60** disposed intermediately in the field of excitation signal **68** produced by resonator **52**. According to an embodiment, the change in the resonance frequency and quality factor due to the presence of sample **60** is used to determine a complex permeability for sample **60** in view of a known geometry of sample **60**. According to an embodiment, the change in the resonance frequency and quality factor of resonator **52** due to presence of sample **60** in the field of excitation signal **68** is used to determine a thickness or geometric property for sample **60** having a known complex permittivity or complex permeability. Moreover, a loss tangent for sample **60** can be determined.

Noncontact resonameter **50** advantageously can be used to measure properties of sample **60** that is involved in a processing or manufacturing facility that includes a web, roll-to-roll, or liquid handling, wherein a feed rate or speed sample **60** conveyed in such environment is several kilometers per hour and continuously producing materials that are used in commercial applications such as pharmaceutical, chemical, or materials manufacturing. Here, the property of sample **60** (e.g., materials properties that correlate to electrical conductivity or dielectric constant) is determined during operation and online using noncontact resonameter **50** that provides a nondestructive, noncontact inline test for the property or quality control of conditions involving sample **60**. Beneficially, noncontact resonameter **50** provides a nondestructive electromagnetic (e.g., microwave) or acoustic resonator **52** to measure the property of sample **60** such as dielectric constant or electrical conductivity, at production speeds with a responsivity to change or absolute determination of the property in real time or at a selected interval of time (e.g., on a microsecond time scale). Moreover, a portion of sample **60** or substantially all of sample **60** can be subjected to excitation signal **60** such that resonator signal **70** includes data pertinent to the portion or all of sample **60** provided intermediately to the field of excitation signal **68** produced by resonator **52**. Furthermore, the property of sample **60** can be determined quantitatively or qualitatively.

In an embodiment, noncontact resonameter **50** is used to determine the electrical property of sample **60** from the resonance frequency or quality factor from resonator signal **70** produced by resonator **52**. Without wishing to be bound by theory, a process for determining the electrical property includes applying a cavity perturbation equation (e.g., discussed below) to resonator signal **70** data. Cavity perturbation equations relate resonance frequency and quality factor of resonator **52** to electrical properties of sample **60** and include properties of resonator **52** such as a sample volume or geometry of resonator **52**. As shown in FIG. **25**, continuous feeder **56** includes web **118** that is continuously communicated through resonator **52**. Waveguide **74** of resonator **52** has dimensions that include cavity height a, cavity thickness d, and cavity width l. Web **118** of continuous feeder **52** (or sample **60**) has dimensions that include sample height h, sample thickness t, and the sample width w. FIG. **26** shows a portion of a longitudinal cross-section in an x-z plane that includes continuous feeder **52** top and waveguide **74**. FIG. **27** shows a transverse cross-section in a y-z plane that includes continuous feeder **52** and waveguide **74**.

The cavity perturbation equations are derived from Maxwell's equations and solved for a real part of complex permittivity (ϵ_r) and an imaginary part of the complex permittivity (ϵ_i) of the sample. The real part of the dielectric constant is provided by formula (1).

$$\frac{\omega_c - \omega_{cs}}{\omega_c} \approx 2 \cdot \left(\frac{V_s}{V_c}\right)(\epsilon_r - 1) + b_r. \quad (1)$$

wherein in formula 1 ω_c, is the resonance frequency of resonator **52**; ω_{cs} is the resonance frequency of resonator **52** in a presence of sample **60** or continuous feeder **52**; V_c is the volume of the cavity of resonator **52**; V_s is the effective volume of sample **60** or continuous feeder **52** disposed in the cavity of resonator **52**; and b_r is an intercept. The effective sample volume V_{cs} is effective because the electromagnetic field of excitation signal **68** is distributed non-uniformly over sample **60**. Here, waveguide **74** is a cavity having a rectangular shape, which has an electromagnetic mode of a resonance provided by parameter n. In some embodiments, effective sample volume Vs is provided by formula (2),

$$V_s = h \cdot \left(\frac{t}{2} + \frac{d}{2\pi}\sin\left(\frac{\pi t}{d}\right)\right) \cdot \left(\frac{w}{2} + \frac{\ell}{2\pi n}\sin\left(\frac{n\pi w}{\ell}\right)\right) \quad (2)$$

wherein h is sample height; t is sample thickness; w is sample width; a is cavity height; d is cavity thickness; and l is cavity width. Cavity volume V_c is provided by formula (3),

$$V_c = a \cdot d \cdot l. \quad (3)$$

The imaginary part of the dielectric constant is provided by formula (4),

$$\frac{1}{Q_{cs}} - \frac{1}{Q_c} \approx 4 \cdot \left(\frac{V_s}{V_c}\right)\epsilon_i + b_i. \quad (4)$$

wherein Q_c is the quality factor of resonator **52**; Q_{cs} is the quality factor of resonator **52** having sample **60** or continuous feeder **56** disposed in waveguide **74**; and b_i is an intercept. In some embodiments, intercepts b_r and b_i account for parasitic fields and can constant or finitely small (e.g., substantially having a value that is close to zero).

The articles and processes herein are illustrated further by the following Examples, which are non-limiting.

EXAMPLES

Example 1. Continuous Measurement of First Voltage (First Output Signal) and Second Voltage (Second Output Signal)

A noncontact resonameter as shown in FIG. **24** was provided and included circuit **54** as shown in FIG. **12**. The in-phase signal of lock-in amplifier **106** was processed with proportional-integrator-derivative controller **110**, as shown in FIG. **12**. Proportional-integrator-derivative controller **110** produced first output signal **46** that was recorded as sample **60** was continuously fed through resonator **52**. Three measurements were made with noncontact resonameter **50** for first output signal **46**. In a first measurement, first output signal **46** was measured without sample **60** disposed in resonator **52**. In a second measurement, sample **60** included web **118** that was fabricated to include a polyimide strip that was 70 cm long. An amplitude of first output signal **46** (measured as a voltage) was shifted by approximately a constant relative to the amplitude of first output signal **46** from resonator **52** without sample **60**. The polyimide web **118** was communicated through resonator **52** at a feed rate of 18 cm/s for a length of 50 cm of sample **60**. A staircase pattern of sample **60** was made wherein the polyimide was formed in steps having 6 cm lengths with an equivalent thickness increase per step. As a result of varying thickness of polyimide sample **60**, the amplitude of first output signal **46** shifted by an increasing amount relative to the amplitude of first output signal **46** measured from resonator signal of resonator **52** without sample **60** disposed therein. FIG. **28**, FIG. **29**, and FIG. **30** show graphs of voltage amplitude of first output signal **46** versus position along sample **60** respectively for empty resonator **52** (absence of sample **60** in resonator **52**), monotonic thickness sample **60**, and sample **60** that had a staircase pattern with incremental thickness.

The magnitude signal of lock-in amplifier **108** was processed by proportional-integrator-derivative controller **114** (see FIG. **12**), and controller **114** produced second output signal **48** that was obtained as sample **60** was continuously fed through resonator **52**. Noncontact resonator **50** made three measurements for second output signal **48**. In a first measurement, second output signal **48** was measured without sample **60** disposed in resonator **52**. In a second measurement, sample **60** included web **118** that was fabricated to include a polyimide strip that was 70 cm long. An amplitude of second output signal **48** (measured as a voltage) was shifted by approximately a constant relative to the amplitude of second output signal **48** from resonator **52** without sample **60**. The polyimide web **118** was communicated through resonator **52** at a feed rate of 18 cm/s for a length of 50 cm of sample **60**. A staircase pattern of sample **60** was made wherein the polyimide was formed in steps having 6 cm lengths with an equivalent thickness increase per step. As a result of varying thickness of polyimide sample **60**, the amplitude of second output signal **48** shifted by an increasing amount relative to the amplitude of second output signal **48** measured from resonator signal **70** of resonator **52** without sample **60** disposed therein. FIG. **31**, FIG. **32**, and FIG. **33** show a graph of voltage amplitude of second output signal **48** versus position along sample **60** respectively for empty resonator **52** (absence of sample **60** in resonator **52**), monotonic thickness sample **60**, and sample **60** that had a staircase pattern with incremental thickness.

The amplitude of first output signal **46** related to the resonance frequency of resonator **52**, and the amplitude of the second output signal **48** related to the quality factor of resonator **52**. Where first output signal **46** and second output signal **48** are voltages, first output signal **46** and second output signal **48** can be used directly without and further analysis of data to determine, e.g., a relative change in resonant frequency or change in quality factor.

Example 2. Calibration of Circuit to Obtain Resonant Frequency and Quality Factor of Resonator

Circuit **54** was used to calibrate the resonance frequency and quality factor of resonator **52** of the noncontact resonator of Example 1. The calibration quantitatively related first output signal **46** (e.g., an amplitude of its voltage) and second output signal **48** (e.g., an amplitude of its voltage) measured by circuit **54** to the resonance frequency and quality factor of resonator **52**. The calibration was performed in two sets of measurements. In the first measurement, sample **60** was disposed in resonator **52** in a plurality of discrete steps in which the amount of sample **60** disposed in an interior of resonator **52** increased from 0% to 100%. At each insertion, a vector network analyzer measured scattering parameters of resonator **52** as a function of frequency.

The scattering parameters were fit to a damped harmonic oscillator model as a function of frequency. FIG. **34** shows a graph of magnitude of the transmission $|S_{21}|$ versus frequency, and FIG. **35** shows a graph of the phase S_{21} of the transmission versus frequency. The damped harmonic oscillator equation provided an amplitude and phase such that transmission T is $T(\omega)=A(\omega)e^{i\Phi(\omega)}$, wherein $A(\omega)$ is the amplitude as provided in formula (5), and $\phi(\omega)$ is the phase as provided in formula (6).

$$A(\omega) = \frac{2A_o\zeta\omega_o^2}{(\omega_o^2 - \omega^2)^2 + (2\zeta\omega_o\omega)^2} \quad (5)$$

-continued

$$\phi(\omega) = -\arctan\left(\frac{2\zeta\omega_o\omega}{\omega_o^2 - \omega^2}\right) + m_o\omega + \phi_o \quad (6)$$

Amplitude A(ω) included three fit parameters, i.e., amplitude A_o of the signal, resonance frequency ω_o, and damping ratio ζ. Phase φ(ω) included two fit parameters, i.e., delay m_o, and phase offset ϕ_o. The scattering parameters were fit to formula (5) and formula (6) as a function of frequency. Here, ω_o was the resonance frequency of resonator **52**, and the damping ratio was related to the quality factor of resonator **52** as 1/2ζ.

After the quality factor and resonance frequency of resonator **52** was determined as a function of insertion percentage of sample **60** in resonator **52**, first output signal **46** and second output signal **48** were measured with sample **60** disposed in resonator **52** at the same selected insertion values.

FIG. **36** shows a graph of resonance frequency of resonator **52** versus first output signal **46**, and a best fit line to the data is also shown. FIG. **37** shows a graph of quality factor of resonator **52** versus second output signal **48**, and a best fit line to the data is also shown.

Example 3. Continuous Measurement of Resonance Frequency and Quality Factor of the Resonator

From the best fit lines of resonance frequency and quality factor shown in FIG. **36** and FIG. **37**, the best fit lines were used to map from first output signal **46** and second output signal (shown in FIG. **28** to FIG. **33**) to the resonance frequency and quality factor, respectively. The result of this mapping is shown in FIG. **38**, FIG. **39**, FIG. **40** (for resonance frequency versus position of sample **60** disposed in resonator **52**) and shown in FIG. **41**, FIG. **42**, and FIG. **43** (for quality factor versus position of sample **60** disposed in resonator **52**). In certain applications, such as quality control, the resonance frequency and quality factor are used directly without further analysis of the data.

Example 4. Continuous Measurement of Complex Permittivity or Dielectric Constant and Conductivity

Once the resonance frequency and quality factor of resonator **52** were recorded for polyimide sample **60** per Example 3, the real part of the complex permittivity was determined from formula (1). FIG. **44** shows a graph of the real part of the complex permittivity of polyimide sample **60** that was determined at an excitation signal frequency of 10 GHz for a length of 50 cm of sample **60** that was provided to resonator **52** at a feed rate of 18 cm/s through opening **78** in resonator **52**. The real part of the complex permittivity was determined to be about 3.1, which was consistent with reported value of provided by the manufacturer of sample **60** at this frequency.

FIG. **45** shows a graph of the imaginary part of the complex permittivity versus position of polyimide sample **60** determined at 10 GHz for a 50 cm length of sample **60** that moved at a feed rate of 18 cm/s through resonator **52**.

In some embodiments, both real and imaginary parts of the complex permittivity are extracted to obtain the loss tangent. FIG. **46** shows a graph of the loss tangent versus a position of polyimide sample **60**. The loss tangent was determined as a ratio of the imaginary part of the complex permittivity to the real part of the complex permittivity.

Example 5. Sample Thickness Measurement

The sample volume or a particular geometrical factor can be extracted for quality assurance and control applications. Formula (1) and formula (4) are inverted to solve for the effective sample volume for sample **60** with known real or imaginary complex permittivity. The volume of sample **60** solved from the resonance frequency of resonator **52** is provided by formula (7), and the volume of sample **60** determined from the quality factor of resonator **52** is provided by formula (8).

$$V_s \approx \left(\frac{V_c}{2\cdot(\epsilon_r - 1)}\right)\cdot\left(\frac{\omega_c - \omega_{cs}}{\omega_c} - b_r\right) \quad (7)$$

$$V_s \approx \left(\frac{V_c}{4\epsilon_i}\right)\cdot\left(\frac{1}{Q_{cs}} - \frac{1}{Q_c} - b_i\right) \quad (8)$$

After formula (7) and formula (8) were numerically evaluated, formula (2) was solved for the sample geometry. The thickness of polyimide sample **60** with varying thickness was determined at 10 GHz using formula (7), and FIG. **47** shows a graph of thickness versus position of sample **60**.

Example 6. Sheet Resistance Measurement

A sheet resistance or conductivity of sample **60** can be extracted for a quality assurance or control application. Here, the imaginary part of the complex permittivity relates to the effective sample conductivity as provided by formula (9),

$$\sigma \approx \epsilon_i \epsilon_o \omega_{cs} \quad (9)$$

wherein the permittivity of the free space, ϵ_o, is approximately $8.85\cdot10^{-12}$ Farads/meter. For sample **60** of known thickness t, the sheet resistance R relates to sample conductivity as provided by formula (10).

$$R \approx t/\sigma \quad (10)$$

Two conducting thin films were used as samples. Electrical properties of the films were measured using a direct current four-point probe. The direct current four-point probe required that the sample was measured at different positions along the film. Once the sample was measured with the direct current four-point probe, the conducting thin films were measured by the noncontact resonameter of Example 1. FIG. **48** shows a graph of sheet resistance versus position of sample **60** with respect to resonator **52**. Here, the noncontact resonameter provided sheet resistance values that were within twice the uncertainty of the direct current four-point probe measurement.

Example 7. Isolating the Contribution of an Unknown Layer in a Multilayered Sample

Properties of samples that contain a plurality of layers can be determined with the noncontact resonameter of Example 1. Such samples can include, e.g., of a stack of layers, concentric circular layers, or a weave of fibers. The effect of the known layers to measurement with the noncontact resonameter can be subtracted from the total measured voltages (e.g., of first output signal **46** or second output signal **48**) or the resonance frequency and quality factor of

resonator **52**. In an embodiment, the effect of the known layers contributes to the resonance frequency and quality factor as a parallel admittance. The total measured resonance frequency is provided by formula (11), and the quality factor is provided by formula (12).

$$\omega_{total}^{-2}=\omega_{unknown}^{-2}+\omega_{known}^{-2}+\omega_{c}^{-2} \quad (11)$$

$$Q_{total}^{-1}=Q_{unknown}^{-1}+Q_{known}^{-1}+Q_{c}^{-1} \quad (12)$$

Formula (11) and formula (12) can be used to obtain the left hand side of formula (1) and formula (4), respectively.

Example 8. Magnetic Properties Measurement

In some embodiments, magnetic properties of sample **60** are determined. Formula (1) and formula (4) are modified accordingly to extract the complex permeability. Accordingly, the change in the resonance frequency and quality factor of resonator **52** are due to the magnetic properties of sample **60** and the sample volume.

While one or more embodiments have been shown and described, modifications and substitutions may be made thereto without departing from the spirit and scope of the invention. Accordingly, it is to be understood that the present invention has been described by way of illustrations and not limitation. Embodiments herein can be used independently or can be combined.

Reference throughout this specification to "one embodiment," "particular embodiment," "certain embodiment," "an embodiment," or the like means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment. Thus, appearances of these phrases (e.g., "in one embodiment" or "in an embodiment") throughout this specification are not necessarily all referring to the same embodiment, but may. Furthermore, particular features, structures, or characteristics may be combined in any suitable manner, as would be apparent to one of ordinary skill in the art from this disclosure, in one or more embodiments.

All ranges disclosed herein are inclusive of the endpoints, and the endpoints are independently combinable with each other. The ranges are continuous and thus contain every value and subset thereof in the range. Unless otherwise stated or contextually inapplicable, all percentages, when expressing a quantity, are weight percentages. The suffix "(s)" as used herein is intended to include both the singular and the plural of the term that it modifies, thereby including at least one of that term (e.g., the colorant(s) includes at least one colorants). "Optional" or "optionally" means that the subsequently described event or circumstance can or cannot occur, and that the description includes instances where the event occurs and instances where it does not. As used herein, "combination" is inclusive of blends, mixtures, alloys, reaction products, and the like.

As used herein, "a combination thereof" refers to a combination comprising at least one of the named constituents, components, compounds, or elements, optionally together with one or more of the same class of constituents, components, compounds, or elements.

All references are incorporated herein by reference.

The use of the terms "a" and "an" and "the" and similar referents in the context of describing the invention (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. "Or" means "and/or." Further, the conjunction "or" is used to link objects of a list or alternatives and is not disjunctive; rather the elements can be used separately or can be combined together under appropriate circumstances. It should further be noted that the terms "first," "second," "primary," "secondary," and the like herein do not denote any order, quantity, or importance, but rather are used to distinguish one element from another. The modifier "about" used in connection with a quantity is inclusive of the stated value and has the meaning dictated by the context (e.g., it includes the degree of error associated with measurement of the particular quantity).

What is claimed is:

1. A noncontact resonameter comprising:

a resonator to:

produce an excitation signal comprising a field;

subject a sample to the excitation signal;

produce a first resonator signal in a presence of the sample and the excitation signal, the first resonator signal comprising:

a first quality factor of the resonator;

a first resonance frequency of the resonator; or

a combination comprising at least one of the foregoing,

the first resonator signal occurring in an absence of contact between the sample and the resonator; and

produce a second resonator signal in a presence of the excitation signal and an absence of the sample, the second resonator signal comprising:

a second quality factor of the resonator;

a second resonance frequency of the resonator; or

a combination comprising at least one of the foregoing;

a circuit in electrical communication with the resonator to receive the first resonator signal and the second resonator signal, the circuit comprising:

a diode that:

receives the first resonator signal and the second resonator signal from the resonator; and

produces a detector signal in response to receipt of the first resonator signal or the second resonator signal;

a tunable resistor in electrical communication with the diode and that:

receives the detector signal from the diode;

controls a signal-to-noise ratio of the circuit; and

tunes a measurement speed of the circuit;

a first phase sensitive detector in electrical communication with the diode and that:

receives the detector signal from the diode;

receives a frequency output from a frequency source;

samples at a first harmonic of the frequency output from the frequency source;

produces in-phase signal in response to receipt of the detector signal and the frequency output;

a process controller in electrical communication with the first phase sensitive detector and that:

receives the in-phase signal from the first phase sensitive detector; and

produces a first output signal in response to receipt of the in-phase signal;

a bias tee in electrical communication with the frequency source and the process controller and that:

receives the frequency output from the frequency source;

receives the first output signal from the process controller; and

produces a control signal in response to receipt of the frequency output and the first output signal;

a second phase sensitive detector in electrical communication with the diode and that:

receives the detector signal from the diode;

receives the frequency output from the frequency source;

samples at a second harmonic of the frequency output from frequency source; and

produces a magnitude signal in response to receipt of the detector signal and the frequency output;

the frequency source in electrical communication with the first phase sensitive detector and the second phase sensitive detector and that:

produces the frequency output;

controls a modulation frequency of a source signal produced by a source oscillator;

a second process controller in electrical communication with the second phase sensitive detector and that:

receives the magnitude signal from the second phase sensitive detector; and

produces a second output signal in response to receipt of the magnitude signal, the second output signal being communicated to the frequency source to control an amplitude of the frequency modulation of the source oscillator by changing an amplitude of the frequency source;

a continuous feeder to:

provide the sample proximate to the resonator;

dispose the sample intermediately in the field of the excitation signal during production of the first resonator signal;

remove the sample from the resonator;

manipulate a position of the sample relative to the resonator in a continuous motion and in an absence of contact between the sample and the resonator; and

a source in electrical communication with the resonator and that comprises:

the source oscillator that:

receives the control signal from the bias tee;

tunes selectively a center frequency of the source signal;

produces the source signal in response to receipt of the control signal; and

provides the source signal to the resonator, such that:

the resonator receives the and produces the excitation signal in response to receipt of the,

wherein the circuit is in electrical communication with the and produces a control signal in response to receipt of the first resonator signal, and

the comprises a phase and an amplitude that are based on the control signal, such that the circuit provides feedback to the source to detect a change in resonance frequency or quality factor of the resonator.

2. The noncontact resonameter of claim **1**, wherein

a first harmonic of output power from the resonator signal produced by the resonator locks a center frequency of the excitation signal to a resonance frequency of resonator by changing an amplitude of the first output signal; and

a second harmonic of output power from the resonator signal produced by the resonator adjusts a depth of the frequency modulation of the source signal by tuning the second output signal.

3. The noncontact resonameter of claim **1**,

wherein a power difference between a maximum and a minimum output power during a modulation cycle is constant, and

the second output signal is monotonically related to a quality factor of the resonator.

4. The noncontact resonameter of claim **1**, wherein the resonator comprises a free-space resonator or a cavity resonator.

5. The noncontact resonameter of claim **4**, wherein the resonator is the cavity resonator, and the cavity resonator comprises:

a wall bounding a sample space to receive the sample; and

an opening to transmit the sample to the sample space.

6. The noncontact resonameter of claim **4**, wherein the resonator is the free-space resonator, and the free-space resonator comprises a sample space to receive the sample.

7. The noncontact resonameter of claim **1**, wherein the continuous feeder traverses the resonator.

8. The noncontact resonameter of claim **1**, wherein the circuit comprises a plurality of phase sensitive detectors to receive the first resonator signal and the second resonator signal.

9. The noncontact resonameter of claim **1**, wherein the field of the excitation signal comprises an electromagnetic field or an acoustic field.

10. The noncontact resonameter of claim **1**, wherein the first resonance frequency changes with a change in the dielectric constant of the sample subjected to the excitation signal, and the first quality factor changes with a change in the electrical conductivity of the sample subjected to the excitation signal.

11. The noncontact resonameter of claim **1**, wherein the continuous feeder provides continuously a first portion of the sample to the resonator and removes continuously a second portion of the sample from the resonator.

12. The noncontact resonameter of claim **1**, wherein the continuous motion is interruptible.

13. The noncontact resonameter of claim **1**, wherein the continuous motion occurs substantially in a single dimension of travel of the sample relative to the resonator, from provision of the sample to the resonator to removal of the sample from the resonator.

14. The noncontact resonameter of claim **1**, wherein the noncontact resonameter provides a measurement of a property of the sample, the property comprising an electrical property, a mechanical property, a geometric property, or a combination comprising at least one of the foregoing properties,

the property determined from the first resonator signal.

15. The noncontact resonameter of claim **14**, wherein the property is the electrical property, and

the electrical property comprises a permittivity, a dielectric constant, an electrical conductivity, a permeability, or a combination comprising at least one of the foregoing electrical properties.

16. The noncontact resonameter of claim **1**, wherein the circuit detects the first quality factor and the first resonance frequency simultaneously in real time in the presence of the sample, and

the circuit detects the second quality factor and the second resonance frequency simultaneously in real time in the absence of the sample.

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