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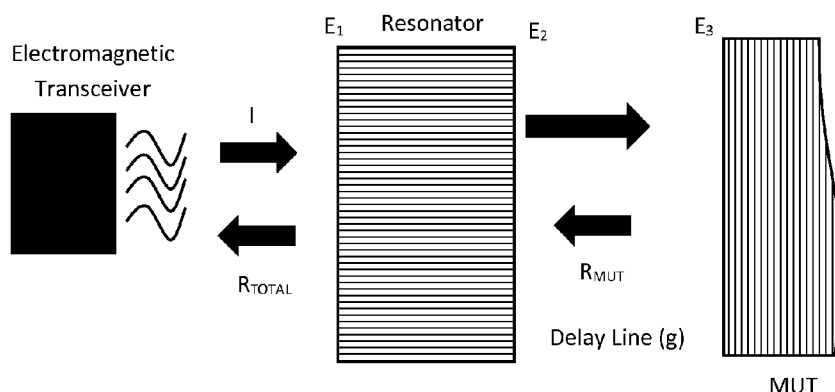
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(54) **Title:** ENHANCED CHARACTERIZATION OF DIELECTRIC PROPERTIES

**FIG. 5**

(57) **Abstract:** A sensor for sensing a reflection or transmission property of a material, the sensor comprising an electromagnetic radiation input means for creating or receiving an electromagnetic radiation signal, a resonator for influencing the electromagnetic radiation input signal, a material holder for holding the material under test, a delay line positioned between the resonator and the material holder such that the electromagnetic radiation travels in the delay line after passing the resonator and prior to reaching the material under test, when it is positioned in the material holder, and a detection means for detecting a signal reflected by or transmitted through the material under test.



Enhanced characterization of dielectric properties

Field of the invention

The invention relates to the field of sensing. More specifically it relates to methods and systems for sensing dielectric properties of materials using reflection or transmission measurements.

5 Background of the invention

The dielectric permittivity of a material depends on particular properties such as for example its composition and its temperature. Since physical changes such as moisture loss, protein denaturation, etc. take place during processing for example industrial processing and since these affect the dielectric properties of materials, the process or thereof can be followed by
10 monitoring or evaluating changes in dielectric permittivity.

Monitoring or evaluating changes in dielectric permittivity may for example be performed using an electromagnetic measurement system or sensor. One example of a system or sensor for measuring dielectric properties changes in material is based on detection of electromagnetic wave reflection coefficients. Existing sensor solutions measure changes in the
15 reflection coefficient to determine the material properties (e.g. moisture, temperature, overall composition, and etc.). Nevertheless, the changes in reflection coefficient due to material property changes are small and often cannot distinguish subtle change. Existing electromagnetic sensor solutions like free-space electromagnetic measurements often use a simple antenna configuration, as shown in FIG. 1. Open resonators, like a Fabry-Perot require
20 the material under test (MUT) to be loaded into the resonator, as shown in FIG. 2, this imposes conditions on sample size, placement. Similarly, open-ended electromagnetic transmission-lines can be used for material characterization as shown in FIG. 3, but these solutions also do not feature high sensitivity, while transmission line resonators need to be loaded with the material under test (MUT) inside the transmission line. Yet another known configuration is
25 given, wherein a waveguide configuration is used in FIG. 4. The sensors shown in FIG. 1 and FIG. 3 are wideband but are little sensitive to changes of the dielectric permittivity of the material. The sensors in FIG. 2 and FIG. 4 utilize a resonator to enhance the sensitivity of a conventional open-ended probe. A thin layer of MUT is in direct contact with the resonator and is covered with metal, which imposes limitations on MUT.
30 Consequently, there is still a need for a sensor which allows determining dielectric properties with a high accuracy and resolution.

Summary of the invention

It is an object of embodiments of the present invention to provide sensors, systems and methods for determining dielectric property changes of materials with high sensitivity and high accuracy.

5 It is an advantage of embodiments of the present invention to provide a sensor which is based on detection of reflection or transmission signals but wherein the configuration is adapted such that the changes in an overall reflection or transmission measured are substantially larger than the changes in the reflection or transmission of the material under test, so that an increased sensitivity for the minute change in dielectric permittivity of the material can be obtained.

10 It is an advantage of embodiments according to the present invention that a sensor system and method can be obtained whereby a process, e.g. industrial process can be followed by instantaneous detection of the changes in dielectric permittivity of a material, using reflection or transmission measurements.

The above objective is accomplished by a method and device according to the present
15 invention.

The present invention relates to a sensor for sensing a reflection or transmission property of a material, the sensor comprising an electromagnetic radiation input means for creating or receiving an electromagnetic radiation signal, a resonator for influencing the electromagnetic radiation input signal, a material holder for holding the material under test, a delay line
20 positioned between the resonator and the material holder such that the electromagnetic radiation travels in the delay line after passing the resonator and prior to reaching the material under test, when it is positioned in the material holder, and a detection means for detecting a signal reflected by or transmitted through the material under test. It is an advantage of embodiments according to the present invention that small changes in the reflection
25 properties of a material under test, result in larger changes of the reflection coefficient or transmission coefficient measured for the material under test using the particular configuration of the resonator, the delay line and the material holder.

The sensor may have a free space configuration. It is an advantage of embodiments according to the present invention that a free-space configuration can be used, whereby little or no
30 limitative conditions are posed on the material under test.

The electromagnetic radiation input means may be an electromagnetic radiation source comprising a transmitter.

The sensor may have a waveguide-based configuration, wherein the electromagnetic radiation input is a waveguide portion wherein electromagnetic radiation can be coupled and wherein the resonator is a resonator embedded in the waveguide and wherein at least part of the delay line is positioned in the waveguide. It is an advantage of some embodiments of the present invention that for some applications a waveguide-based configuration can be used.

The system may comprise a transceiver, functioning both as electromagnetic radiation input means and as detection means.

The resonator may be a high quality factor resonator, with a quality factor larger than 10.

The resonator may be a band pass filter.

10 The length of the delay line may be adjustable so as to be able to adjust the sensor to the material under test to be measured.

The material holder may be adapted for adjusting a position of the material under test, so as to adjust the length of the delay line.

15 The present invention also relates to the use of a sensor as described above for detection a change in dielectric properties of a material under test.

The present invention furthermore relates to the use of a sensor as described above for monitoring a change in material composition.

The present invention also relates to the use of a sensor as described above for monitoring a process, e.g. an industrial process.

20 Particular and preferred aspects of the invention are set out in the accompanying independent and dependent claims. Features from the dependent claims may be combined with features of the independent claims and with features of other dependent claims as appropriate and not merely as explicitly set out in the claims.

25 These and other aspects of the invention will be apparent from and elucidated with reference to the embodiment(s) described hereinafter.

Brief description of the drawings

FIG. 1 – prior art describes a free space configuration for detection of reflection signals, as known in the field.

30 FIG. 2 – prior art describes an open resonator configuration based on a Fabry-Perot detection of reflection signals, as known in the field.

FIG. 3 – prior art and FIG. 4 – prior art describe waveguide based open-ended electromagnetic transmission-line configurations for measuring reflection signals, as known in the field.

FIG. 5 illustrates a configuration for accurate detection of reflection of a material under test, according to an embodiment of the present invention.

5 FIG. 6 illustrates an explicit example of a free-space configuration for accurate detection of reflection according to the embodiment as shown in FIG. 5.

FIG. 7 illustrates an explicit example of an open ended electromagnetic transmission-line configuration sensor for detecting of reflection, according to an embodiment as shown in FIG. 6.

10 FIG. 8a and FIG. 8b illustrate the sensitivity of reflection measurements to changes in dielectric properties for a state of the art reflection measurement configuration (FIG. 8a) and a reflection measurement configuration according to an embodiment of the present invention (FIG. 8b).

FIG. 9 illustrates results for transmission measurements for a liquid with varying alcohol concentration, illustrating advantages of embodiments of the present invention.

15 FIG. 10 illustrates a sensor with resonator and delay line positioned before the material under test, according to an embodiment of the present invention.

FIG. 11 illustrates the reflection and transmission coefficient from a dielectric slab in different optical lengths, as can be obtained in embodiments of the present invention.

FIG. 12 illustrates another sensor with a resonator and delay line positioned before the material
20 under test, according to an embodiment of the present invention.

FIG. 13 illustrates a further sensor with a resonator and delay line positioned before the material under test, according to an embodiment of the present invention.

FIG. 14 illustrates the reflection coefficient (S_{11}) as function of the frequency for different moisture contents, illustrating properties that can be measured using embodiments of the
25 present invention.

FIG. 15 illustrates yet another example of a sensor with a resonator and delay line positioned before the material under test, according to an embodiment of the present invention.

FIG. 16 illustrates a CST simulation model of transmission, illustrating features of a method according to an embodiment of the present invention.

30 The drawings are only schematic and are non-limiting. In the drawings, the size of some of the elements may be exaggerated and not drawn on scale for illustrative purposes.

Any reference signs in the claims shall not be construed as limiting the scope.

In the different drawings, the same reference signs refer to the same or analogous elements.

Detailed description of illustrative embodiments

The present invention will be described with respect to particular embodiments and with reference to certain drawings but the invention is not limited thereto but only by the claims. The drawings described are only schematic and are non-limiting. In the drawings, the size of some of the elements may be exaggerated and not drawn on scale for illustrative purposes. The dimensions and the relative dimensions do not correspond to actual reductions to practice of the invention.

Furthermore, the terms first, second and the like in the description and in the claims, are used for distinguishing between similar elements and not necessarily for describing a sequence, either temporally, spatially, in ranking or in any other manner. It is to be understood that the terms so used are interchangeable under appropriate circumstances and that the embodiments of the invention described herein are capable of operation in other sequences than described or illustrated herein.

Moreover, the terms top, under and the like in the description and the claims are used for descriptive purposes and not necessarily for describing relative positions. It is to be understood that the terms so used are interchangeable under appropriate circumstances and that the embodiments of the invention described herein are capable of operation in other orientations than described or illustrated herein.

It is to be noticed that the term “comprising”, used in the claims, should not be interpreted as being restricted to the means listed thereafter; it does not exclude other elements or steps. It is thus to be interpreted as specifying the presence of the stated features, integers, steps or components as referred to, but does not preclude the presence or addition of one or more other features, integers, steps or components, or groups thereof. Thus, the scope of the expression “a device comprising means A and B” should not be limited to devices consisting only of components A and B. It means that with respect to the present invention, the only relevant components of the device are A and B.

Reference throughout this specification to “one embodiment” or “an embodiment” means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, appearances of the phrases “in one embodiment” or “in an embodiment” in various places throughout this specification are not necessarily all referring to the same embodiment, but may. Furthermore, the 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.

Similarly it should be appreciated that in the description of exemplary embodiments of the invention, various features of the invention are sometimes grouped together in a single
5 embodiment, figure, or description thereof for the purpose of streamlining the disclosure and aiding in the understanding of one or more of the various inventive aspects. This method of disclosure, however, is not to be interpreted as reflecting an intention that the claimed invention requires more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive aspects lie in less than all features of a single foregoing
10 disclosed embodiment. Thus, the claims following the detailed description are hereby expressly incorporated into this detailed description, with each claim standing on its own as a separate embodiment of this invention.

Furthermore, while some embodiments described herein include some but not other features included in other embodiments, combinations of features of different embodiments
15 are meant to be within the scope of the invention, and form different embodiments, as would be understood by those in the art. For example, in the following claims, any of the claimed embodiments can be used in any combination.

In the description provided herein, numerous specific details are set forth. However, it is understood that embodiments of the invention may be practiced without these specific
20 details. In other instances, well-known methods, structures and techniques have not been shown in detail in order not to obscure an understanding of this description.

Where in embodiments of the present invention reference is made to a material under test or MUT, reference is made to the material of interest that is to be identified based on dielectric properties or that is to be monitored for identifying properties of the material during
25 a process, e.g. an industrial process, or that is to be monitored for identifying properties of the process, e.g. an industrial process.

For reflection measurements, the material under test or MUT has a reflection coefficient larger than zero. The reflection coefficient S_{11} should be larger than 0.

In a first aspect, the present invention relates to a sensor for detecting a dielectric
30 property of a material under test or a change in dielectric properties of a material under test. The dielectric property may for example be a permittivity of a material, a real and/or imaginary dielectric permittivity, a loss tangent, a real and/or imaginary refractive index, relaxation parameters for a dielectric permittivity model such as a Debye, Cole or Havriliak-Negami model

whereby the relaxation parameters can for example be time constants or strength, etc. According to embodiments of the present invention, the dielectric property is based on a reflection or transmission measurement of the material under test. It thereby is an advantage of embodiments of the present invention that a configuration is used for measuring reflection or transmission whereby small changes in the reflection or transmission properties of the material under test result in significantly larger changes in the overall reflection or transmission measured, such that detection with a high sensitivity can be used. Changes in dielectric properties can be caused by changes to the material under test and consequently, the systems and methods of the present invention allow to detect or follow material changes. Furthermore, if the material changes are imposed by a change in the environmental conditions or during a process, systems and methods may be suitable for monitoring environmental changes or processes, such as for example industrial processes.

According to embodiments of the present invention, the sensor comprises an electromagnetic radiation input means for creating or receiving an electromagnetic radiation signal. Such an electromagnetic radiation input means may be an electromagnetic radiation source allowing generation of electromagnetic radiation, or it may be a receiving means adapted for receiving an electromagnetic radiation, such as for example a waveguide portion adapted for receiving electromagnetic radiation from a source. The radiation source – which may be part or may not be part of the sensor - may be a conventional radiation source emitting electromagnetic radiation at least at frequencies where the reflection/transmission is most sensitive. The radiation source may for example be an oscillator such as for example backward wave oscillators, IMPATT diodes, Gunn diodes, etc., it may for example be a non-linear frequency converters or Multipliers such as harmonic mixers, balanced mixers, etc., it may be for example a phase locked synthesizer, a voltage controlled oscillator or a nonlinear optical mixer (optics to THz). The frequency range wherein the reflection is measured may depend on the size of the object. The frequency range may be in a microwave frequency range, e.g. between a few MHz up to 10 GHz, which can for example be used for bulky objects, may be in the millimeter wave range, e.g. between 10GHz to 100GHz, or may be in the Terahertz range, e.g. between 100 GHz to 10THz. The radiation source may comprise a radiation antenna. It may be a transmitter or may be a transceiver.

The sensor furthermore comprises a resonator for modifying the electromagnetic radiation input signal. The resonator may be a high quality factor resonator. In some embodiments, the resonator may be a band pass filter. The resonator may be one or more

resonant elements. The resonator may be a band-stop filter. The resonator has a quality factor Q larger than 10. The resonance frequency of the filter typically is in the frequency range of interest. The resonator may be under-coupled, critically coupled, or over-coupled. In some embodiments, resonance is caused by the multiple reflections/transmissions at the edges of the resonator.

The sensor also comprises a material holder for holding the material under test (MUT). The material holder may for example be a sample stage, a holder having fixing means for fixing the material on the holder, etc. Advantageously, the material holder allows for displacing the material under test, so that the length of the delay line (which will be further discussed below) can be adjusted.

The sensor according to embodiments of the present invention also comprises a delay line. The delay line is positioned between the resonator and the material holder such that the electromagnetic radiation travels in the delay line after passing the resonator and prior to reaching the material under test, when it is positioned in the material holder.

The delay line may have a length g between the resonator and MUT, which may be selected as function of a dielectric property of the material under test, the thickness of the material under test and the operating frequency used. The length of the delay line may for example be a function of the permittivity of the material measured. The length of the delay line g can be expressed as :

$g = \text{function}(\text{frequency, dielectric property, thickness of material under test})$

wherein g is the length of the delay line, frequency is the working frequency for the sensing, dielectric property is the dielectric property of the material such as for example its permittivity, and thickness of the material under test is the thickness of the material measured in a direction parallel with the incident radiation.

The sensor furthermore typically comprises an electromagnetic radiation detection means for detecting radiation reflected by the MUT, after again passing through the delay line and the resonator. The detection means may be any suitable type of detection means, such as for example broad-band detectors like Schottky Diode detectors or narrow-band detectors like I/Q mixers, subharmonic mixers, etc. The detection means may comprise or be a receiver. In some embodiments, the source and the detector may comprise common parts, for example a transceiver may be present allowing to emit the electromagnetic radiation towards the MUT and allowing to detect reflected or transmitted electromagnetic radiation.

The sensor furthermore may comprise a processing means or processor for converting a detected reflection signal in a dielectric parameter of the MUT. Such a processing means or processor may be part of the sensor or may be external thereto. In some embodiments, such a processor may comprise or be replaced by a programmed algorithm or a look up table.

- 5 Other optional component such as for example a memory, processing means, an output means or display for indicating a result, ... may be present, as known by the person skilled in the art. By way of illustration, an example of the configuration of a sensor according to an embodiment of the present invention is shown in FIG. 5. An electromagnetic radiation source is shown, as well as a resonator. The resonance in the resonator typically may be caused by multiple reflections on the resonator edges (E1 and E2) whereby the specific resonance induced is determined by the reflections on the edges and the resonator length. The reflection R on an edge is determined by the impedance mismatch, given by

$$R = \frac{Z_1 - Z_0}{Z_1 + Z_0}$$

- Impedance on the dielectric resonator edge E2 is determined by the reflection on the edge of MUT (E3) and distance to the MUT (g), as it is given by the following equation:

$$Z_{E2} = \frac{Z_{E2}(1 + \Gamma_{E3} \exp(-2i\beta g))}{(1 - \Gamma_{E3} \exp(-2i\beta g))}$$

where Γ_{E3} is the reflection on the MUT edge (E3), which is dependent on the dielectric permittivity property of MUT, and where β is the wave number.

- 20 The high sensitivity of the sensor is obtained as follows : small changes of Γ_{E3} result in a change in resonator conditions which detunes the resonance and causes a bigger signal change. The resonator conditions thereby may be selected such that preferably a high Q factor of the resonator is obtained, that there is a good band pass reflection response and that it corresponds with a multiple of a half-wave or quarter-wave standing wave.
- 25 In one embodiment, the reflection sensor is a free space sensor comprising a resonator and a delay line in the optical path between the radiation source and the material under test. The free space sensor may be especially suitable for some applications, as it imposes little or no limitations on the shape or other properties of the material under test. As indicated above, the material under test can be any type of material for which dielectric properties are of interest.
- 30 In advantageous embodiments, the evolution of a material under study can be monitored or followed over time.

By way of illustration, an example is shown in FIG. 6.

In another embodiment, the reflection sensor is a waveguide based sensor wherein the electromagnetic radiation is directed to the material under test using a waveguide. The type of waveguide that can be used is a hollow metal pipe waveguide with various cross-sections, such as rectangular, circular, ridge waveguides, etc., parallel plate waveguides, co-planar waveguides. Alternatively transmission lines can be used such as for example coaxial cable transmission lines, micro-strip lines and strip lines, In embodiments based on waveguides or transmission lines the resonator can be a waveguide section or transmission line section with some dielectric object inserted with different dielectric permittivity than the rest of the waveguide or transmission line, a waveguide section or transmission line section with a different cross-section and specific length, a waveguide section or transmission line section that is linked to other waveguide through coupling windows, a combination of these implementations, etc. The characteristics of the resonator may be the same as described above. Between the resonator and the open-ended waveguide side directed to the material under test, a delay line is present. The delay line may be formed by a non-filled portion of the waveguide, between the resonator and the end of the waveguide. Alternatively, the resonator may be positioned at the edge of the open end of the waveguide pointing towards the material under test and the delay may be formed by an open region between the end of the waveguide and the material under test. In yet another embodiment, the delay line is formed by a delay line embedded in the waveguide in combination with an open space between the open-end of the waveguide and the material under test. Such a delay line may have a predetermined length, such that the distance between the resonator and the material under test is appropriate. An example of such a configuration is shown in FIG. 7.

Results

By way of illustration, embodiments of the present invention not being limited thereby, experimental results are discussed below of measurements of reflection coefficients of a material under test as function of changing dielectric properties. In the example given, the change of moisture content in potatoes is measured which influence the permittivity of the potato. Such a change in complex permittivity of the potato occurs for example during a drying process.

By way of illustration, the changes of the complex permittivity of the potato with moisture content is shown in table 1. These changes in complex permittivity are then measured both with a state of the art reflection measurement configuration as shown in FIG. 1 and with a

reflection sensor having a configuration as shown in FIG. 6 according to an embodiment of the present invention.

Reference number	Complex permittivity	Moisture content in the potato (%)
P1	10,6180570681832 - 14,5516269032950i	80,03
P2	8,35803400013808 - 11,2646188096905i	78,48
P3	7,92880027147919 - 10,2943607414067i	75,28
P4	7,55582908941358 - 9,48224418009226i	72,52
P5	7,25948435081575 - 8,84456939153392i	70,15
P6	7,02138392248074 - 8,33498157452024i	68,06

5

Table 1

FIG. 8a illustrates the reflection coefficient that is obtained with a reflection measurement configuration according to the state of the art, shown in FIG. 1, illustrating that the differences in moisture content results in differences small changes in the reflection coefficient, e.g. smaller than 0,2 dB for some moisture changes of 2 to 3%. Nevertheless, for the same moisture changes, the differences in reflection coefficient measured with a system according to an embodiment of the present invention results in a few dB up to more than 10 dB (depending on the specific moisture content). The latter illustrates that reflection measurements according to embodiments of the present invention result in a far better sensitivity to changes in the corresponding dielectric properties. It is to be noticed that the sensitivity of the sensor typically occurs for a selected frequency of frequency band and is not present over the full frequency range. Nevertheless, the system can be easily tuned to such a frequency or frequency band.

Whereas embodiments of the present invention are mainly described with reference to reflection measurements, the same principle is applicable to transmission measurements. By way of illustration, the present invention not being limited thereto, an example of how transmission measurements using a setup comprising a resonator and delay line according to embodiments of the present invention is shown in FIG. 9. FIG. 9 illustrates the effect on transmission for a liquid as function of the percentage alcohol comprised in the liquid. It can

be seen that large differences can be seen in the transmission results that are obtained for alcohol concentrations between 10% and 40%.

Whereas the above example illustrates the possibility of identifying a change in the material content, embodiments of the present invention are not limited thereto. In one example, the system could be used for sensing e.g. pH, since this also influences the reflectivity. Therefore, the present invention also relates to an optical measurement device for sensing pH or pH differences. .

By way of illustration, embodiments of the present invention not being limited thereto, two cases are illustrated, clarifying the working principle of dielectric enhancement techniques in a transmission mode. In the first case, the applied Electromagnetic (EM) wave cannot penetrate the material under test (MUT). In the second case, the applied EM wave can penetrate the MUT.

In case 1, the material under test (MUT) is opaque to applied EM wave or the MUT is infinitely thick, so that no reflection from second boundary of the MUT occurs. Enhancement is possible for an only Reflection measurement method.

When MUT is very thick and/or opaque to applied Electromagnetic (EM) wave, in another words, if there is no reflection from the second boundary of MUT : the total reflection is a function of the resonator parameter, g and the dielectric constant of the material under test.

$$R_{\text{TOTAL}} = f(g, \epsilon_{\text{MUT}}).$$

The different reflections occurring are shown in FIG. 10. In FIG. 10, an EM transceiver 101, a resonator 102, a material under test 103, an incident wave 104, the total reflection 105, the delay line 106, and electric fields E_1 107, E_2 108 and E_3 109. The occurrence of the reflections has been discussed in the section above.

In case 2, the material under test (MUT) is transparent for the applied EM wave, resulting in a reflection from the second boundary of the MUT with pre-define thickness. Enhancement is possible for both Reflection or Transmission measurement methods

When the applied EM wave can penetrate MUT, the dielectric enhancement technique can be applied to increase the sensitivity in both the reflection and the transmission coefficient measurement. The working principle of both modes (reflection and transmission) can be explained by using FIG.11. FIG. 11 illustrates the Reflection and Transmission coefficient from a dielectric slab in different optical length. When a slab has the optical length equals to half

wave length or integral multiple of half wave length, it has an impedance matching at 60 GHz. Reflection coefficient at 60 GHz is quite low. On the other hand, when the same dielectric slab has an optical length that equals to the quarter wave length or any odd integral multiple of quarter wave length, it has impedance miss-matching at 60 GHz. In the latter case the transmission is minimum at 60 GHz. This principle can be used when the MUT is transparent for the applied EM wave.

In order to enhance sensitivity of both the reflection or the transmission coefficient to the minute change in the dielectric properties of the material, a high quality factor Resonator (band pass filter) and a delay line with width g before MUT with pre-defined thickness is introduced.

An example of a setup is shown in FIG. 12. In FIG. 12, an EM transceiver 201, a resonator 202, a material under test 203, an electromagnetic magnetic receiver 204, an incident wave 205, the total reflection 206, the delay line 207, the total transmission 208, electric fields E_1 209, E_2 210, E_3 211 and E_4 212. To measure the transmission coefficient an EM receiver is also placed after MUT. By designing the resonator and delay line for the particular case, either mode of the operation can be achieved. However, this technique cannot be applied to increase the sensitivity for both reflection and transmission coefficients at the same time. Therefore, two cases are discussed below.

In the first sub-case a reflection only method is discussed: This case is similar to case 1, only the thickness of the material needs to be taken into account. In order to enhance sensitivity of the reflection method to the minute change of the dielectric properties of MUT, as depicted in FIG. 13, a high quality factor Resonator (band pass filter) and a delay line with width g before MUT with pre-defined thickness is introduced. In FIG. 13, an EM transceiver 301, a resonator 302, a material under test 303, an incident wave 304, the total reflection 305, the delay line 306, the electric fields E_1 307, E_2 308, E_3 309 and E_4 310.

In this case, the total reflection is a function of the resonator parameters, g , the dielectric constant of the MUT and the thickness of the MUT :

$$R_{\text{TOTAL}} = f(\text{resonator parameters}, g, \epsilon_{\text{MUT}}, \text{Thickness}_{\text{MUT}}).$$

Here, impedance matching condition can occur between the MUT and rest of the system (delay line and resonator). Because of the high Q of the resonator, and as a result of the resonance detuning by the MUT loading conditions, the small change in the MUT causes a bigger change in total reflection (R_{TOTAL}). In this way the sensor can enhance the reflection signal changes and increases the sensitivity of sensor to the minute change in dielectric properties of the MUT. The measured reflection coefficient is determined by the dielectric permittivity of the MUT

with pre-defined thickness. And hence the properties (e.g. moisture content, temperature and etc) can be extracted accurately from the measured reflection coefficient. By way of illustration, the following table shows the permittivity of a material with moisture content starting from 3.9 down to 1.9.

Moisture content %	Complex permittivity of MUT
3,9	2,03970 - 0.1299 i
3,5	2,01953 - 0.1202i
3,1	1,99953 - 0.1107i
2,7	1,97969 - 0.10142i
2,3	1,96002 - 0.0922i
1,9	1,94050 - 0.0833i

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By using the sensor system shown in FIG. 13, the reflection coefficient change w.r.t permittivity of the MUT with thickness 10.07 mm is shown in FIG. 14. FIG. 14 illustrates the reflection coefficient (S_{11}) versus the frequency for different moisture contents.

In subcase 2, the transmission only method is discussed. The sensor system to enhance sensitivity of the transmission coefficient to the minute change in the dielectric properties of MUT with pre-defined thickness is depicted in FIG. 15. FIG. 15 illustrates an EM transceiver 401, a resonator 402, a material under test 403, an EM receiver 404, the incident wave 405, the delay line 406, the total transmission 407, the electric fields E1 408, E2 409, E3 410 and E4 411. This sensor system consists of an EM source, a resonator, a delay line, the MUT and an EM receiver. The applied EM waves passes through the resonator, the delay line and the MUT to the EM receiver. The total transmission T_{TOTAL} can be determine by propagating the transmission coefficient from resonator to MUT.

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In this case the total transmission is a function of the resonator parameters, g , the dielectric constant of the MUT and the thickness of the MUT :

$$T_{TOTAL} = f(\text{resonator parameters, } g, \epsilon_{MUT}, \text{Thickness}_{MUT})$$

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Here, an impedance miss-matching condition can occur between the MUT and rest of the sensor system (delay line and resonator). In this case, a mirror needs to be formed among the resonator, the delay line and the MUT. In this way maximum reflection and minimum transmission can be achieved. Because of the sensitive and designed resonator placed before the MUT, the small change in the MUT cause a bigger change in the total transmission (T_{TOTAL}). In this way the sensor can enhance the transmission signal changes and increase the sensitivity

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of the sensor to minute changes in the dielectric properties of the MUT. Measured transmission coefficient is determined by the dielectric permittivity of the MUT with pre-defined thickness. And hence the properties (e.g. moisture content, temperature and etc.) can also be extracted accurately from the measured transmission coefficient.

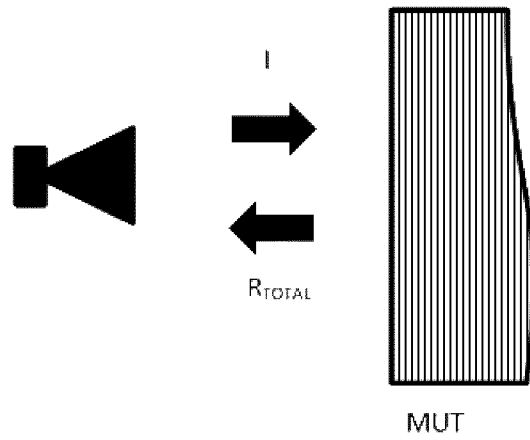
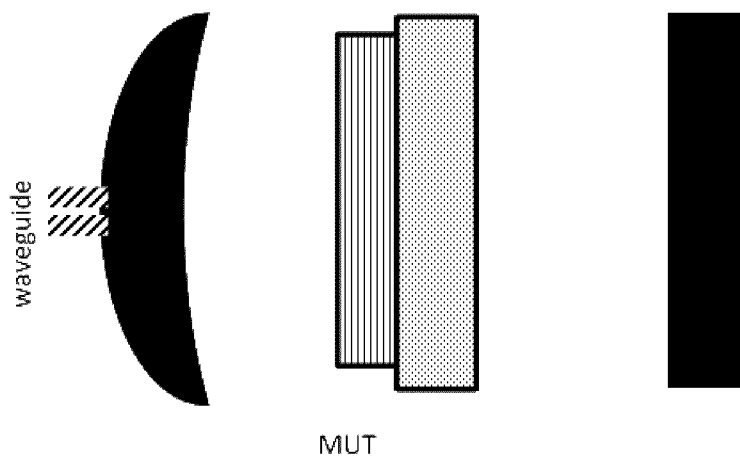
- 5 In an illustrative example for the transmission only method, an EM simulation model was established taking into account an EM wave source, followed by a resonator, followed by a delay line, followed by the material under test and followed by the EM wave receiver (left to right). The CST model for a transmission only method is shown in FIG. 16 and corresponds exactly with the setup shown in FIG. 15. The modelling parameters used in FIG. 16 are given in
- 10 the below table :

e-field	(f = 53,24)
Outplane normal	1, 0, 0
Outplane position	0
Component	Abs
2D Maximum [V/m]	146.4e+03
Frequency	53.24
Phase	0

Claims

1. A sensor for sensing a reflection or transmission property of a material, the sensor comprising
 - an electromagnetic radiation input means for creating or receiving an electromagnetic radiation signal,
 - a resonator for influencing the electromagnetic radiation input signal
 - a material holder for holding the material under test
 - a delay line positioned between the resonator and the material holder such that the electromagnetic radiation travels in the delay line after passing the resonator and prior to reaching the material under test, when it is positioned in the material holder, and
 - a detection means for detecting a signal reflected by or transmitted through the material under test.
2. A sensor according to claim 1, wherein the sensor has a free space configuration.
3. A sensor according to claim 2, wherein the electromagnetic radiation input means is an electromagnetic radiation source comprising a transmitter.
4. A sensor according to claim 1, wherein the sensor has a waveguide-based configuration, wherein the electromagnetic radiation input is a waveguide portion wherein electromagnetic radiation can be coupled, wherein the resonator is a resonator embedded in the waveguide and wherein at least part of the delay line is positioned in the waveguide.
5. A sensor according to any of the previous claims, wherein the sensor is a sensor for sensing a reflection property and wherein the detection means is configured for detecting a signal reflected by the material under test.
6. A sensor according to any of the previous claims, wherein the system comprises a transceiver, functioning both as electromagnetic radiation input means and as detection means.
7. A sensor according to any of the previous claims, wherein the resonator is a high quality factor resonator, with a quality factor larger than 10.
8. A sensor according to any of the previous claims, wherein the resonator is a band pass filter.
9. A sensor according to any of the previous claims, wherein the length of the delay line is adjustable so as to be able to adjust the sensor to the material under test to be measured.

10. A sensor according to claim 9, wherein the material holder is adapted for adjusting a position of the material under test, so as to adjust the length of the delay line.
11. Use of a sensor according to any of claims 1 to 10 for detection a change in dielectric properties of a material under test.
- 5 12. Use of a sensor according to any of claims 1 to 10 for monitoring a change in material composition.
13. Use of a sensor according to any of claims 1 to 10 for monitoring a process, e.g. an industrial process.
14. Use of a sensor according to any of claims 1 to 10 for determining a pH of a material under
10 test.

**FIG. 1 – prior art****FIG. 2 – prior art**

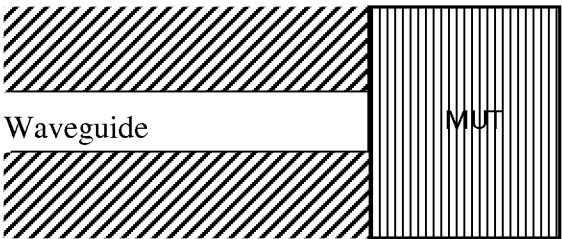


FIG. 3 – prior art

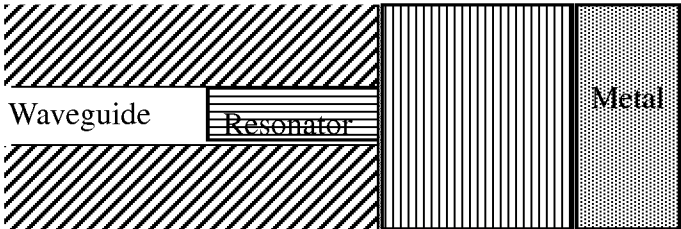


FIG. 4 – prior art

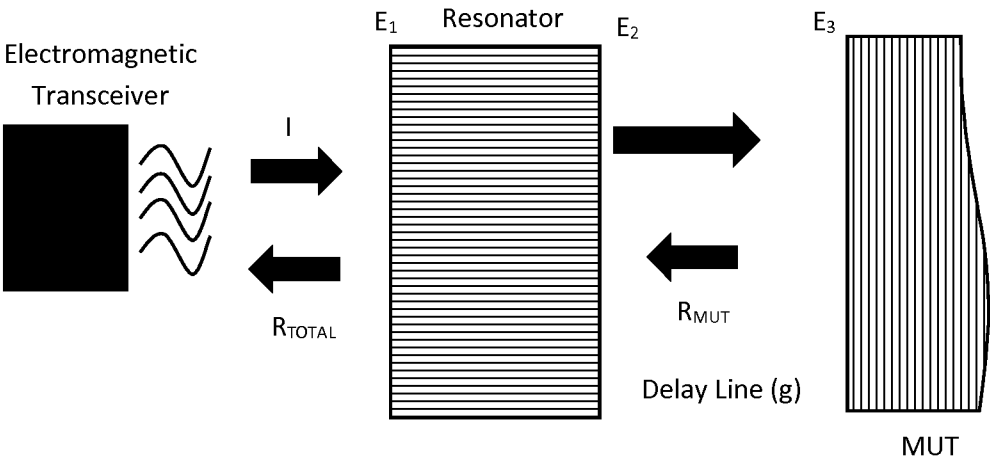


FIG. 5

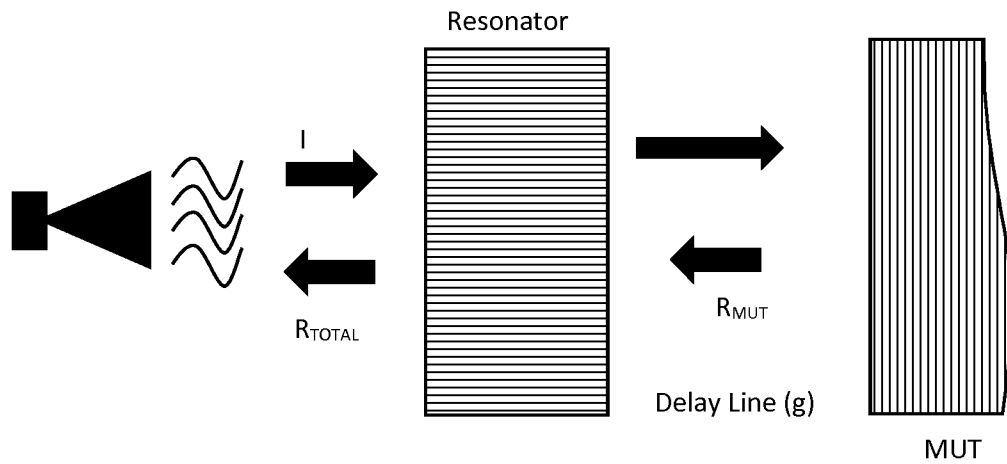


FIG. 6

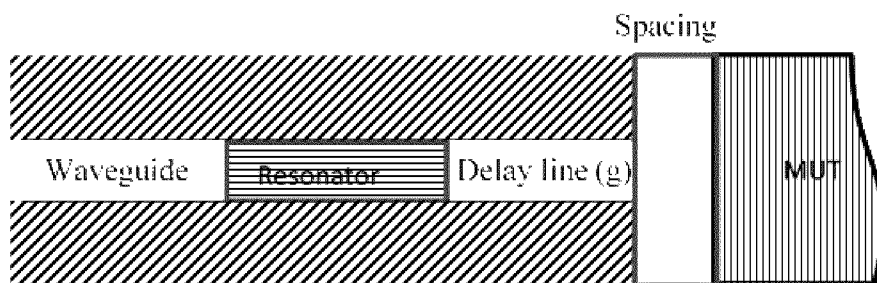


FIG. 7

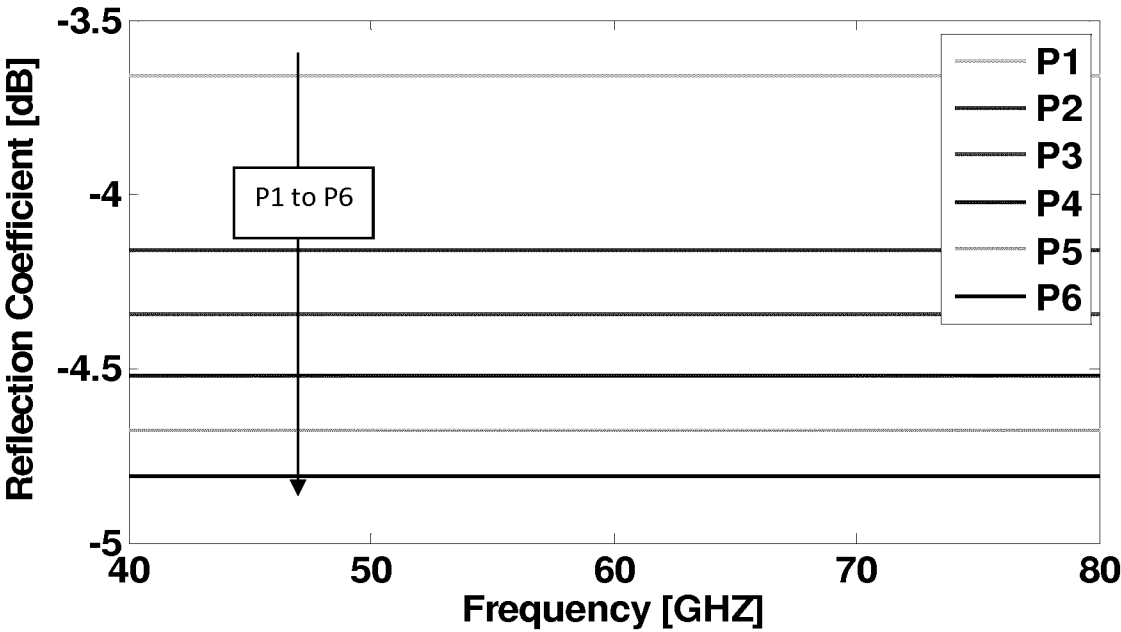


FIG. 8a

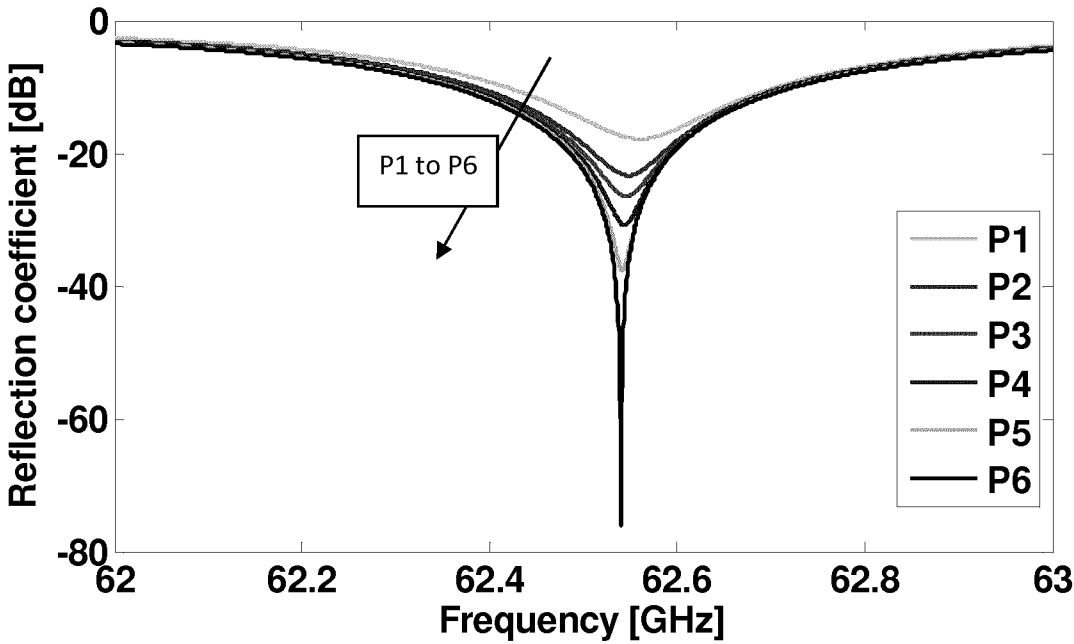


FIG. 8b

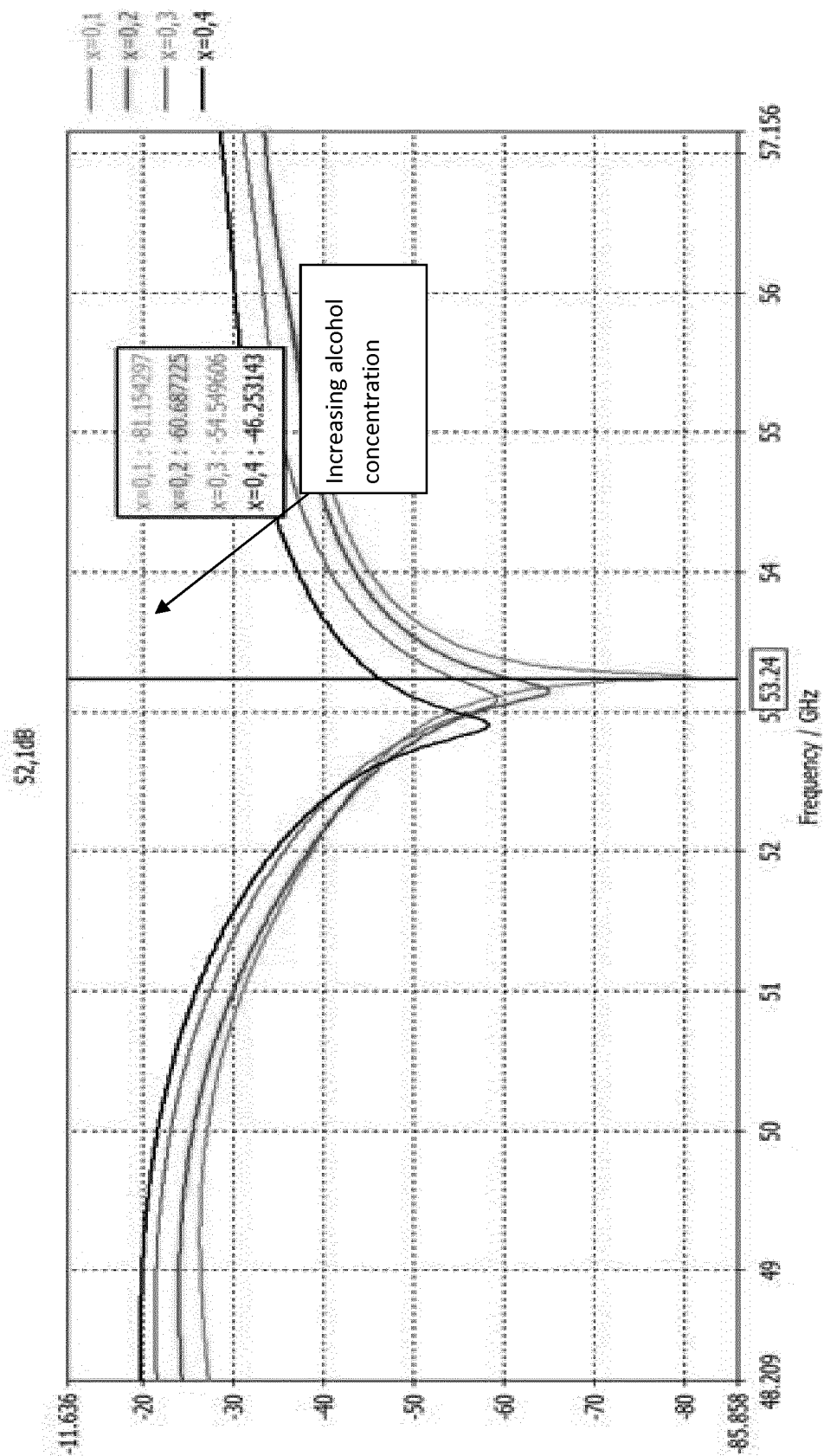


FIG. 9

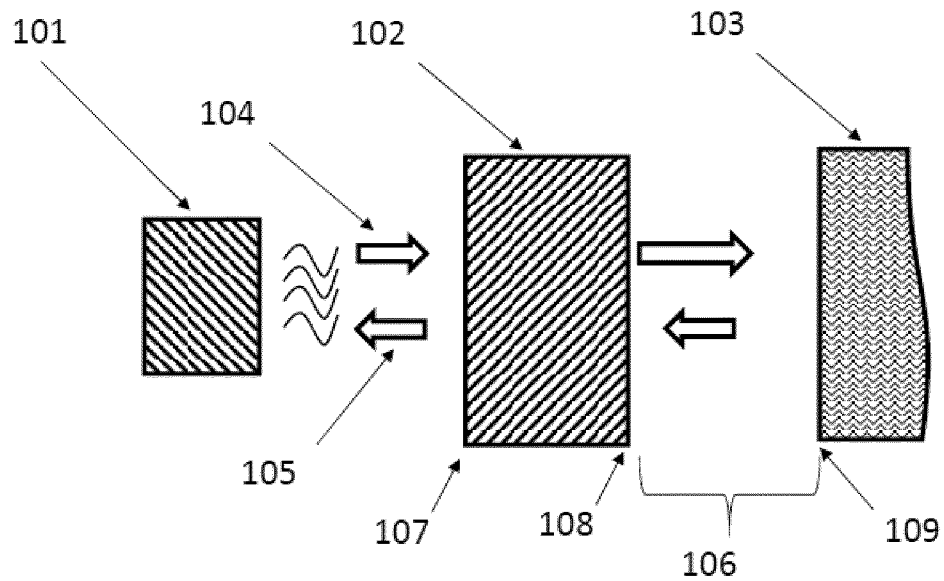


FIG. 10

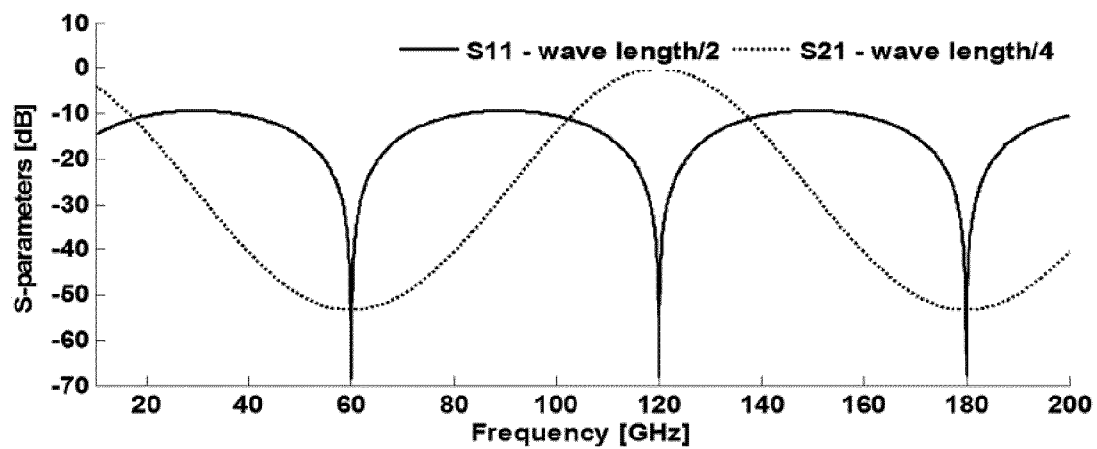


FIG. 11

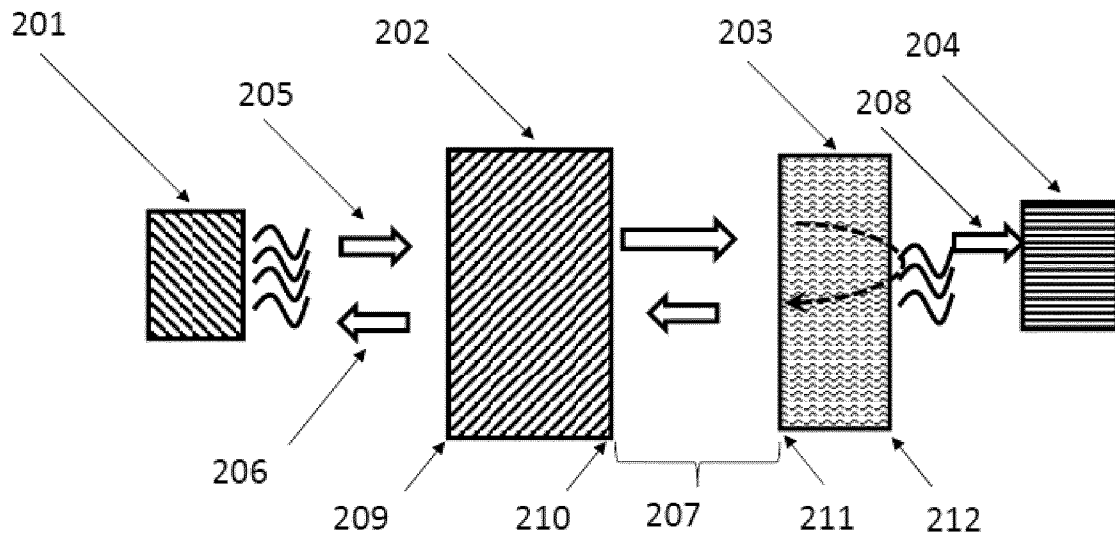


FIG. 12

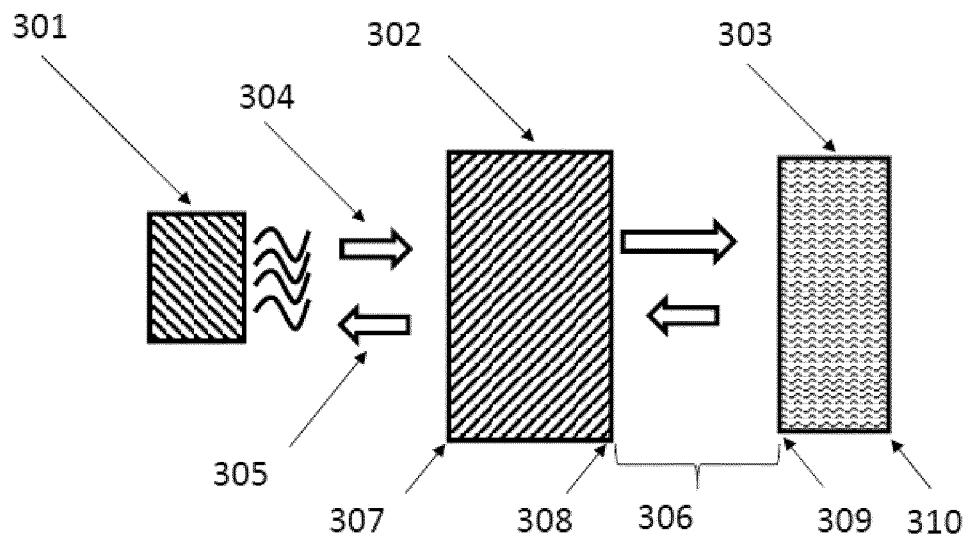


FIG. 13

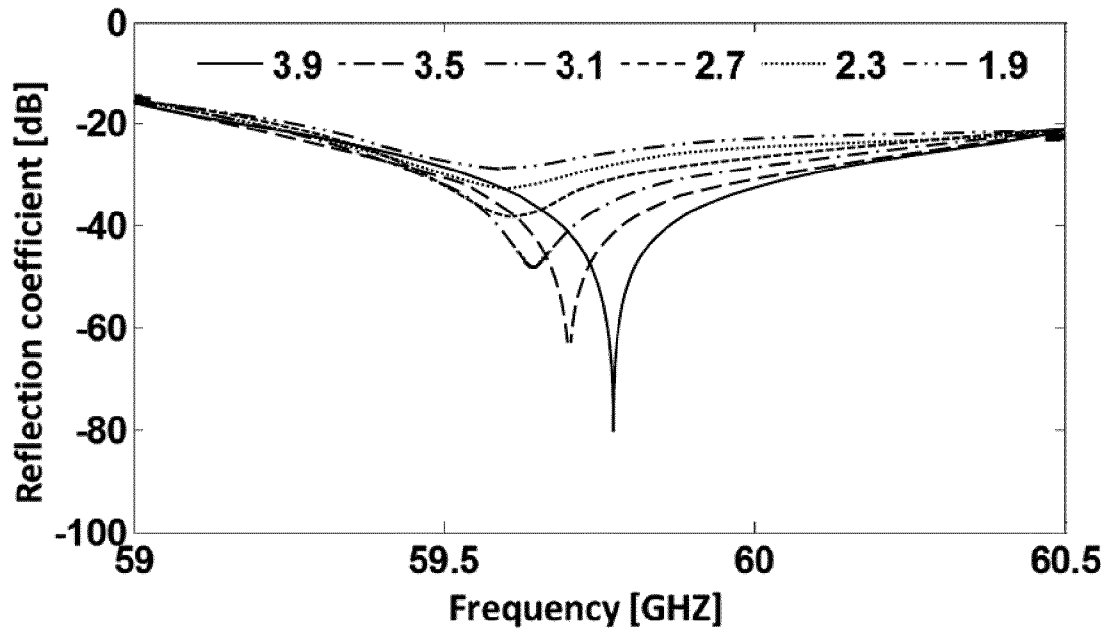


FIG. 14

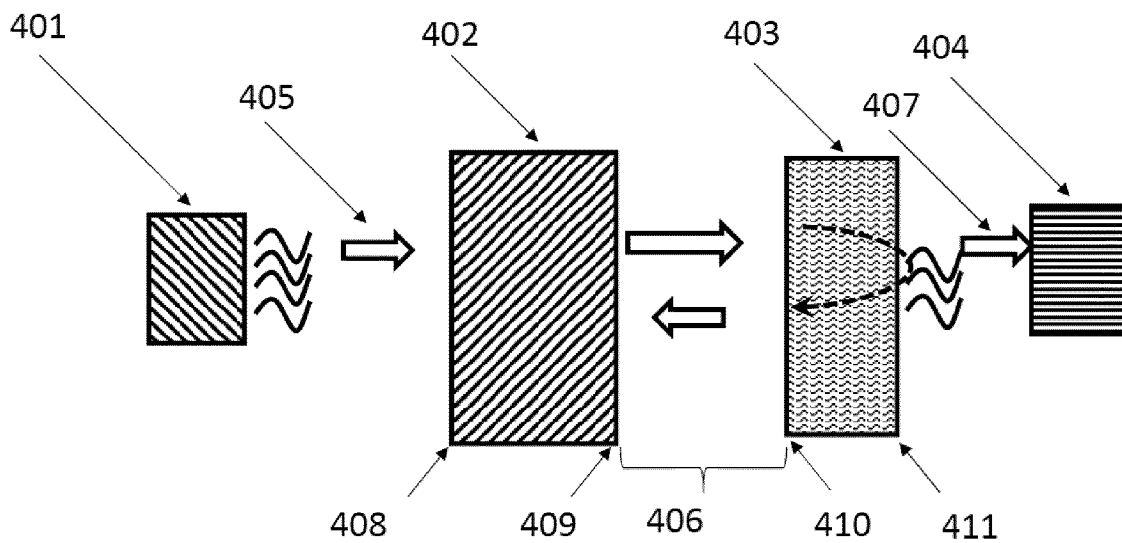
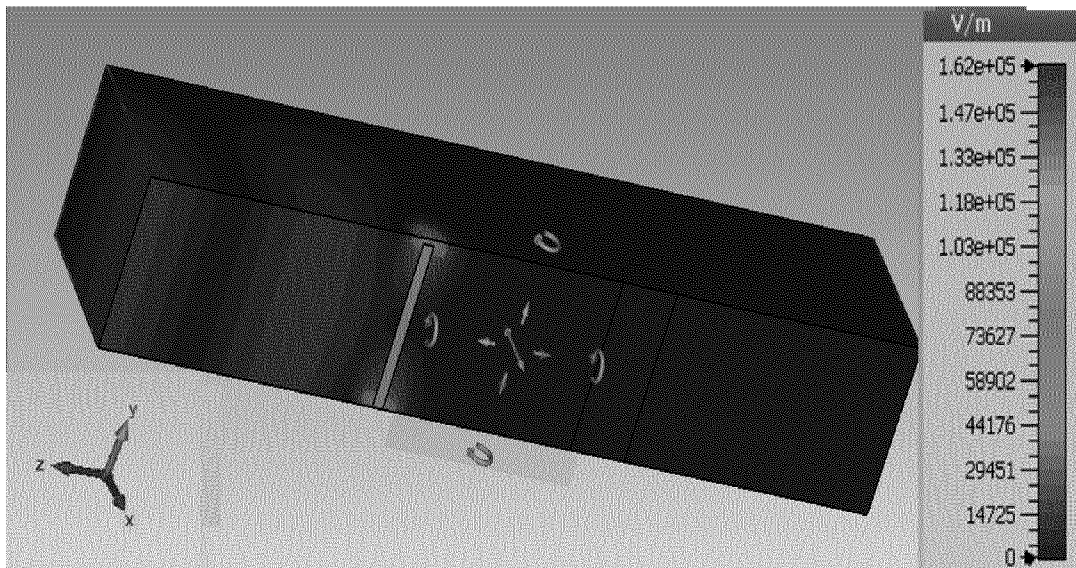


FIG. 15

**FIG. 16**

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/074523

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01N22/00 G01R27/26
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01N G01R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 6 204 670 B1 (JOSHI KALPANA KESHAV [IN]) 20 March 2001 (2001-03-20) column 1, line 1 - line 11 column 4, line 39 - column 5, line 15 figures	1-14
A	----- US 2015/168314 A1 (EL MATBOULY HATEM [CA] ET AL) 18 June 2015 (2015-06-18) paragraph [0002] - paragraph [0003] paragraph [0006] - paragraph [0009]	1-14
A	----- WO 2013/164627 A1 (UNIV HERIOT WATT [GB]) 7 November 2013 (2013-11-07) page 1, line 4 - line 8 page 3, line 31 - page 4, line 17 page 6, line 18 - page 8, line 5; figure 1 ----- -/--	1-14



Further documents are listed in the continuation of Box C.



See patent family annex.

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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Date of the actual completion of the international search

31 October 2016

Date of mailing of the international search report

07/11/2016

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Authorized officer

Savage, John

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2016/074523

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	GB 2 471 024 A (WIVENHOE TECHNOLOGY LTD [GB]) 15 December 2010 (2010-12-15) page 1, line 7 - line 29 page 6, line 3 - line 28; figure 1 -----	1-14
A	US 3 851 244 A (MOUNCE G) 26 November 1974 (1974-11-26) column 1, line 1 - line 24 column 3, line 18 - line 62; figures -----	1-14

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2016/074523

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			US 2001030543 A1	18-10-2001

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