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Quantum-based device including vapor cell

Abstract

In one example, a system includes a first sealed container, a second sealed container, a signal coupler, a container enclosure, and an electromagnetic (EM) reflective coating. The first sealed container encloses a first dipolar gas. The second sealed container encloses a second dipolar gas. The signal coupler is communicatively coupled between the first and second sealed containers. The signal coupler includes a solid material or a hollow sealed tube. The container enclosure encloses the first and second sealed containers and the signal coupler. The EM reflective coating is inside the container enclosure and covers at least part of the first container, at least part of the second container, and at least part of the signal coupler.

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Background/Summary

RELATED APPLICATION

(1) The present application is related to U.S. Provisional Patent Application No. 63/419,375, titled “Quantum Sensor and Integration with Microelectronic Devices”, filed on Oct. 26, 2022, and U.S. Provisional Patent Application No. 63/383,971, titled “Quantum Sensor and Integration with Microelectronic Devices”, filed on Nov. 15, 2022, which are hereby incorporated herein by reference in their entireties.

BACKGROUND

(2) A vapor cell (or a physics cell) can include a hermetically sealed container containing a gas. A vapor cell may be useful in numerous applications, including as part of a chip-scale millimeter-wave atomic clock. The gas within a vapor cell can contain dipolar molecules at a relatively low pressure that can be chosen to provide a narrow signal absorption frequency peak indicative of the quantum transition molecules as detected at an output of the cavity. An electromagnetic (EM) signal can be launched into the cavity through an aperture in the cavity that is electromagnetically translucent or substantially transparent. Closed-loop control can dynamically adjust the frequency of the signal to match the molecular quantum rotational transition. The frequency of the quantum rotational transition of the selected dipolar molecules may vary less due to aging of the chip-scale millimeter-wave atomic clock and with temperature or other environmental factors, which makes the system useful to provide an accurate clock source that also has long-term stability. It is advantageous to increase the absorption of the EM signal by the dipolar gas, which can increase the signal-to-noise ratio (SNR) and improve the accuracy of the closed-loop control and the determination of the transition frequency. One way to increase the signal absorption by the gas is to increase the propagation distance of the EM signal within the cavity.

SUMMARY
(3) In one example, a system includes a first sealed container, a second sealed container, a signal coupler, a container enclosure, and an electromagnetic (EM) reflective coating. The first sealed container encloses a first dipolar gas. The second sealed container encloses a second dipolar gas. The signal coupler is communicatively coupled between the first and second sealed containers. The signal coupler includes a solid material or a hollow sealed tube. The container enclosure encloses the first and second sealed containers and the signal coupler. The EM reflective coating is inside the container enclosure and covers at least part of the first container, at least part of the second container, and at least part of the signal coupler.
(4) In another example, a system includes a substrate, a first sealed container, a second sealed container, a signal coupler, a container enclosure, and an EM reflective coating. The substrate includes a transmitter and a receiver. The first sealed container encloses a first dipolar gas. The first sealed container has a first end communicatively coupled to the transmitter. The second sealed container encloses a second dipolar gas. The second sealed container has a second end communicatively coupled to the receiver. The signal coupler is communicatively coupled between the first and second sealed containers. The signal coupler includes a solid material or a hollow sealed tube. The container enclosure encloses the first and second sealed containers and the coupler. The EM reflective coating is inside the container enclosure and covers at least part of the first sealed container, at least part of the second sealed container, and at least part of the signal coupler.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) FIG. **1** is a block diagram of an example quantum transition frequency detector.
(2) FIG. **2** is a diagram of an example laser cutting and sealing process for sealing gas-filled glass vials.
(3) FIG. **3** is a cross-sectional top-down view of one end of an example vial.
(4) FIG. **4** is a scattering parameter (S-parameter) graph that illustrates example variation of transmitted EM signal power with respect to frequency in the example quantum transition frequency detector of FIG. **1**.
(5) FIGS. **5**A, **5**B, **5**C, **5**D, **5**E, **5**F, and **5**G show various perspective views of dipolar-gas-confining containers communicatively coupled by a signal coupler, in which the containers are held parallel to each other in a container enclosure.
(6) FIGS. **6**A, **6**B, **6**C, and **6**D show various perspective views of dipolar-gas-confining containers communicatively coupled by a signal coupler, in which the containers are held angled from each other in a container enclosure.
(7) FIGS. **7**A, **7**B, **7**C, **7**D, and **7**E show various perspective views of other example arrangements of dipolar-gas-confining containers communicatively coupled together by a signal coupler.
(8) FIGS. **8**A, **8**B, **8**C, and **8**D show various perspective views of another arrangement of dipolar-gas-confining containers and a signal coupler, in which a first portion of one container is on a second portion of another container, and the signal coupler is positioned between and communicatively couples together respective opposing surfaces of the containers.
(9) FIGS. **9**A, **9**B, **9**C, and **9**D show various perspective views of another arrangement of dipolar-gas-confining containers and a signal coupler, in which a first portion of one container is on a second portion of another container, and the signal coupler is positioned between and couples together respective non-opposing surfaces of the containers.
(10) FIGS. **10**A and **10**B show an oblique parallel projection and side views, respectively, of a portion of an example quantum transition frequency detector, with shading representative of an

electric field that is perpendicular to the direction of propagation.
(11) FIGS. **11**A, **11**B, **11**C, and **11**D show various views of an example quantum transition frequency detector having multiple dipolar-gas-confining containers that are parallel to each other and that have rectangular cross sections, in which the narrower sides are coplanar with each other.
(12) FIGS. **12**A, **12**B, **12**C, and **12**D show various views of an example quantum transition frequency detector having multiple dipolar-gas-confining containers that are angled from each other and that have rectangular cross sections, in which the narrower sides are coplanar with each other.
(13) FIGS. **13**A, **13**B, **13**C, **13**D, and **13**E show various perspective views of respective portions of an example quantum transition frequency detector incorporating at least four dipolar-gas-confining containers and at least three signal couplers collectively arranged in an M-shape or W-shaped configuration, depending on perspective.
(14) FIG. **14** is a top view of an arrangement of an example quantum transition frequency detector having at least six overlapping dipolar-gas-confining containers communicatively coupled together using at least five signal couplers.
(15) FIGS. **15**A, **15**B, and **15**C show angled and side views, respectively, of an example quantum transition frequency detector having dipolar gas-confining containers communicatively coupled together by a signal coupler, in which the containers are arranged perpendicular to (or angled from) a PCB containing transmit and receive antennas and circuitries.
(16) FIGS. **16**A,**16**B, and **16**C show angled and side views, respectively, of an example quantum transition frequency detector having two dipolar-gas-confining containers communicatively coupled together by a signal coupler, in which the containers are arranged perpendicular to (or angled from) a PCB containing transmit and receive antennas and circuitries.
(17) FIGS. **17**A, **17**B, and **17**C show angled and top views, respectively, of an example quantum transition frequency detector having two dipolar-gas-confining containers and communicatively coupled together by a signal coupler, in which the containers are arranged perpendicular to (or angled from) a PCB containing transmit and receive antennas and circuitries.
(18) FIGS. **18**A and **18**B illustrate additional example signal couplers between dipolar-gas-confining containers, in which the containers are communicatively coupled to another arrangement of transmit and receive antennas, which can be Vivaldi antennas.
(19) FIGS. **19** and **20** illustrate additional examples of a container enclosure.
(20) The same reference numbers or other reference designators are used in the drawings to designate the same or similar (functionally and/or structurally) features. The figures are not necessarily drawn to scale.

DETAILED DESCRIPTION

(21) FIG. **1** is a block diagram of an example quantum transition frequency detector **100** that can be integrated to provide, for example, a clock that is accurate to within one second in several hundred years. In other examples, the frequency detector **100** is useful to create a magnetic field sensor (magnetometer), an electric field sensor, or a pressure sensor. Detector **100** includes a container **102**, or an assembly that includes multiple such containers. The container **102** is hermetically sealed to contain a dipolar gas at a relatively low pressure, the precise pressure depending on which dipolar gas is used, among other factors. In some examples, the pressure is less than the atmospheric pressure at sea level. In some examples, the pressure is less than one one-hundredth of atmospheric pressure at sea level. In some examples, the pressure is less than one one-thousandth of atmospheric pressure at sea level. In some examples, the pressure is less than one ten-thousandth of atmospheric pressure at sea level. Suitable dipolar gases can include water vapor (H_2O), acetonitrile (CH_3CN), cyanoacetylene (HC_3N), ammonia (NH_3), carbonyl sulfide (OCS), hydrogen cyanide (HCN), and hydrogen sulfide (H_2S). In some examples, container **102** may be a glass (e.g., borosilicate) tube, as described further with reference to FIG. **2**.
(22) The container **102** (or each container in an assembly) can be coated on the outside with an

electromagnetically reflective (e.g., electrically conductive) material (e.g., a metal), or the container **102** (or each container in an assembly) can be placed in an enclosure that is made of or coated with an electromagnetically reflective material such that exterior walls of the container adjoin (e.g., are substantially in contact with) the electromagnetically reflective material of the enclosure. As examples, the enclosure can be metal or metal-coated plastic. As examples, metallization of the container **102** or the enclosure can be done by sputtering or by evaporation. A single container, or multiple containers assembled in an enclosure, can form a vapor cell. Transmitter (TX) and receiver (RX) antennas (**104**, **106**) are coupled to the container **102** at electromagnetically translucent or substantially transparent windows or container-end access points to respectively launch into the container(s) **102** and receive from the container(s) **102** millimeter-wave electromagnetic radiation that courses through the container(s) **102**.

(23) Circuitry **108** coupled to the antennas (**104**, **106**) provides a closed loop that can sweep the frequency of millimeter-wavelength electromagnetic waves (e.g., between about 20 GHz and about 400 GHz, e.g., between about 70 GHz and about 180 GHz) radiated to the dipolar gas molecules confined in the containers **102**. An absorption at the particular frequency of a quantum transition of the dipolar gas molecules can be observed as a decrease in the power transmitted between transmitter and receiver, and specifically, as a dip in transmitted power at a particular frequency (or a set of frequencies) within the swept frequency range. Iteratively locking to the bottom of the dip provides the quantum transition frequency of the molecules of the confined gas, of which the transition frequency can be relatively stable with respect to the age of the hermetic container, the temperature, and other environmental factors. The stability permits detector **100** to be used for creating accurate quantum references and clocks, the accuracy of which is not substantially reduced with device age or changes in operating environment. Circuitry **108** can include, for example, a voltage-controlled oscillator (VCO) or a digital controlled oscillator (DCO) to generate millimeter waves at a particular frequency that is adjusted until the frequency matches the reference peak absorption frequency (the frequency location of the transmitted power dip).

(24) Linear dipolar molecules have rotational quantum absorption at regular frequencies. As an example, OCS exhibits a transition approximately every 12.16 GHz. A vapor cell as described herein thus can make use of any of the many available quantum transitions in the millimeter-wave frequency range. Circuitry **108** can further include, for example, a divider to divide down the matched frequency, which can be in the tens or hundreds of gigahertz, to a lower output clock frequency, e.g., about 100 MHz. The use of millimeter waves can eliminate (or reduce) the need for a laser as a quantum transition interrogation mechanism, reducing cost and complexity of detector **100** over devices requiring lasers. Operation within the aforementioned frequency ranges permits the transmitter and receiver antennas (**104**, **106**) to be of lengths less than, for example, 10 millimeters, 5 millimeters, or 1 millimeter, depending on the quantum transition frequency of the dipolar gas selected. The container **102** (or each container used in an assembly of containers) can each measure between, for example, about 1 centimeter and about 20 centimeters in length, or about 2 centimeters and about 10 centimeters in length. The container **102** (or each container used in an assembly of containers) can each measure less than about 1 centimeter in dimensions of width and height. In a case where the container **102** is shaped as a circular, elliptical, or rectangular cross-section tube, it can also have a diameter of less than about 1 centimeter. Because quantum absorption increases with container length, with longer container lengths providing for a better-defined observed quantum transition, the length of the container **102** can be limited by fabrication limitations and system package size limitations. Meandering or serpentine-shaped vapor cells can provide longer effective container length within a more compact system package size either by using a bent (e.g., U-shaped) container or by coupling together multiple containers.

(25) FIG. **2** is an illustration of an example laser cutting and sealing process **200** for sealing gas-filled glass vials, as may be used in detector **100** of FIG. **1**. Prior to the cutting and sealing process **200** illustrated in FIG. **2**, a glass (e.g., borosilicate) tube can be fabricated using, as examples, an

extrusion process, a Danner process, a Vello process, a down-draw, or any suitable process. The tube may then be filled with a dipolar gas at low pressure to a purity. To achieve a desired gas purity, a successive vacuum approach can be used to purge air from inside the tube and to eliminate molecules coating the walls of the tube by chemisorption or physisorption. A baking process can also be used prior to cutting and sealing process **200** to eliminate molecules that are absorbed to the internal surface of the tube. Process **200** achieves hermeticity by completely sealing each gas-containing glass vial as it is cut from the tube, and preserves gas purity in part by using a laser cutting process that ensures only local heating, so as to avoid denaturing the contained gas.

(26) In the illustrated example **200**, a directed laser beam **202** cuts and seals a continuous glass (e.g., borosilicate) tube, which can have been manufactured, e.g., by extrusion, into smaller hermetically sealed glass vials each filled with gas at low pressure. The vials can be circular in cross-section, as illustrated in FIG. **2**, or, or in other examples, can be square, rectangular, rounded rectangular, oval, ellipsoid, or other shapes in cross-section. Laser beam **202** is illustrated as separating vial **206** from tube portion **204**. Previously in process **200**, the laser beam **202** separated vial **208** from a glass tube that included tube portion **204** as well as then not-yet-sealed-and-separated vial **206**. Subsequently in process **200**, the laser beam **202** can separate tube portion **204** into additional separate sealed dipolar gas containing glass vials (not shown). Vial **208** is shown in cut-away in FIG. **2** to show trapped gas molecules **210** inside vial **208**. Vial **208** can, for example, be cut from the tube that included tube portion **204** and vial **206** at a thinned portion **212** of the tube. Alternatively, vials can be sealed and cut by locally heating and softening the tube (e.g., using a laser) and then pinching the softened portion of the tube using a mechanical clamp. The same clamp may also cut the vial, or the vial can be cut using a separate tool.

(27) Vials cut from the tube in process **200**, e.g., vials **208** and **206**, can undergo further manufacturing steps, such as exterior metallic coating, and photolithographic etching or laser ablating into the coating of launch and receive windows. In some examples, no metallization of the vials is performed, but instead, each vial is, in a subsequent part of the manufacturing process, placed into an enclosure that is either made of an electromagnetically reflective material (e.g., metal) or is interiorly coated with an electromagnetically reflective material (e.g., metallized) such that when a vial is seated in the enclosure, metal adjoins (e.g., is substantially in contact with) the outside of the glass walls of the vial.

(28) Because the interior of the tube from which each vial is cut is filled with dipolar gas at low pressure, once the glass of the tube melts from the laser energy, the outside pressure compresses and sinks the tube at the point of cutting, which heals sealed subsequent to the removal of the laser beam **202**. The laser beam **202** may heat the glass to temperatures of more than 650° C. in the cutting process, which temperatures may be enough to decompose the contained dipolar gas. Such decomposition can be a non-reversible process that can cause loss of the ability to obtain a quantum absorption at the expected frequency. However, the heating is local, and does not propagate more than a few millimeters during the short time that laser energy is applied. Because the contained gas is low-pressure, it is not very thermally conductive. Only a small amount of the gas in the vicinity of the laser cutting can be denatured by the heating incurred by the laser cutting and sealing process. Each vial cut and sealed during the process may be a centimeter long or more, so the majority of the gas inside each vial maintains its chemical integrity during the cutting and sealing process. The thermal insulation of the glass, as well as that of the low-pressure gas itself, protects the bulk of the gas from thermal denaturing.

(29) FIG. **3** is a view **300** of one end of an example 2 mm wide vial **302** after having been cut and sealed using a laser cutting and sealing method to confine a dipolar gas at the interior **304** of the vial **302**. In this example, the illustrated end of vial **302** is blunt or flat and has an outer surface **306** and an inner surface **308**. In the example shown in FIG. **3**, the outer surface **306** and the inner surface **308** are flat. In some other examples, the outer surface **306** may be concave, and the inner surface **308** may be convex. The illustrated end of vial **302** also has or is proximate to a window

region **310**, which representatively shows an electromagnetically translucent or substantially transparent access point that may be used to respectively launch into the vial **302** or receive from the vial **302**. As explained with reference to FIGS. **1** and **2**, in some examples, the window region **310** may correspond to an opening within an exterior metallic coating applied directly on the vial **302**. In some examples, the window region **310** may correspond to an opening within an electromagnetically reflective material (e.g., metallized) coating applied to the inner surfaces of an enclosure into which vial **302** is placed, such that when vial **302** is seated in the enclosure, metal adjoins (e.g., is substantially in contact with) the outside of the glass walls of the vial **302** and window region **310** is proximate to the illustrate end of vial **302**.
(30) FIG. **4** is a graph **400** that illustrates example variation of transmitted EM signal power with respect to frequency in quantum transition frequency detector **100**. As described above with reference to FIG. **1**, a millimeter-wavelength EM signal is transmitted by TX antenna **104** into dipolar gas-filled container **102**, and the EM signal propagates through container **102** and reaches RX antenna **106**. As the frequency of the EM signal is swept, at the particular frequency of a quantum transition of the dipolar gas molecules can be observed as a decrease in the power transmitted between transmitter and receiver, and specifically, as a dip in transmitted power at a particular frequency (or a set of frequencies) within the swept frequency range. Referring to graph **400**, a dip in transmitted power from 100% to 94% can be observed at 121.6 GHz, which can be the quantum transition frequency. The bandwidth of the dip is about 1 MHz.
(31) To improve the accuracy of the quantum transition frequency determination, it is advantageous to increase the absorption of the EM signal (and the dip) by the dipolar gas and reduces the transmitted power at the quantum transition frequency. Such arrangements can reduce the likelihood of mistaking dips caused by noise as dips caused by absorption of the EM signal, and increase the signal-to-noise (SNR) ratio.
(32) One way to increase the absorption of the EM signal by the dipolar gas at the quantum transition frequency is by increasing the EM signal propagation distance within container **102** between TX antenna **104** and RX antenna **106**. In a case where container **102** includes a straight sealed tube such as shown in FIG. **2**, the length of the sealed tube can be increased to increase the signal propagation distance. But the target dimensions of quantum transition frequency detector **100** (or the target dimensions of the system that includes quantum transition frequency detector **100**) may impose a limit on the maximum length of the sealed tube. Conversely, fitting a long sealed tube as container **102** into quantum transition frequency detector **100** may also lead to unreasonable/unsatisfactory aspect ratio of detector **100** (or the system that includes detector **100**). The tube may be bent to fit into a particular area/aspect ratio, but the process of bending the tube may collapse the interior of the tube at the bent location(s) and compromise the structural integrity of the tube.
(33) As to be described in the following examples, a dipolar gas can include multiple straight sealed vials that are mechanically coupled together by signal couplers. The signal coupler can include a dielectric material, or the same material as the vial (e.g., plastic, epoxy, glass, etc.). The signal coupler can also be filled with a solid material (e.g., dielectric material, or same material as the vial), or can be filled with a gas (e.g., air). The signal coupler can operate as a waveguide, in which the EM signal can propagate between two sealed glass vials via the dielectric signal coupler. With such arrangements, the straight sealed glass vials and the dielectric signal couplers can fit into a particular area/aspect ratio while providing elongated transmission path for the EM signal.
(34) FIGS. **5**A through **5**G show various perspective views of respective portions of an example quantum transition frequency detector **500**, similar in material respects to detector **100** of FIG. **1**. For example, FIG. **5**A is an oblique parallel projection view of detector **500** and FIGS. **5**B and **5**C are top views and side views, respectively, of detector **500**.
(35) Detector **500** incorporates at least two dipolar gas-confining containers **502**, **504** communicatively coupled together via a signal coupler **506**, all of which are enclosed within a

container enclosure **508**. In some examples, signal coupler **506** is in physical contact with containers **502**, **504**. In some examples, signal coupler **506** can be separated from containers **502**, **504** by air gaps. Container enclosure **508** is mechanically coupled to a substrate, such as a printed circuit board (PCB) **514**, or other package substrate having circuitry disposed thereon, including transmit circuitry **516** and receive circuitry **518**. For example, container enclosure **508** can be mounted to PCB **514** by pin or screw (or other securing device) or can be glued thereon.

(36) Gas-confining containers **502**, **504** may each be similar in material respects to container **102** of FIG. **1**, vials **206**, **208** of FIG. **2**, or vial **302** of FIG. **3**. In this example, containers **502**, **504** are parallel to each other and extend, together with signal coupler **506**, on the same plane (e.g., x-y plane) within container enclosure **508**. Signal coupler **506** has a surface **507** facing and proximate end surfaces **509** and **511** of, respectively, containers **502** and **504**, in a U-shaped configuration. Signal coupler **506** can include a solid material or a hollow sealed tube. Signal coupler **506** can be made of a dielectric material (e.g., plastic, epoxy, air, a combination thereof, etc.), a glass material, etc., and can be made of a same of a different material from containers **502** and **504**. An EM signal can propagate from transmit circuitry **516** through container **502**, end surface **509**, surface **507**, signal coupler **506**, surface **507**, end surface **511**, container **504**, and reach receive circuitry **518**, as indicated by dotted line **519**.

(37) FIG. **5**F and FIG. **5**G illustrate alternative examples of signal coupler **506**. In the example shown in FIG. **5**F, the outer surfaces of signal coupler **506**, together with the outer surfaces of containers **502** and **504**, can be coated with an electromagnetically reflective material (e.g., metallized), which is represented in dotted shade in FIG. **5**F, to confine the EM signal within containers **502**, **504**, and signal coupler **506**. Signal coupler **506** can include openings **550** and **552** on surface **507**. Opening **550** interfaces with (and may or may not be in physical contact with) end surface **509** of container **502**, and opening **552** interfaces with end surface **511** of container **504**. Openings **550** and **552**, together with end surfaces **509** and **511**, can be uncoated, or otherwise coated with an electromagnetically translucent or substantially transparent material, to allow EM signal to propagate through opening **550** and end surface **509** and through opening **552** and end surface **511**.

(38) FIG. **5**G illustrates another example of signal coupler **506**. In the example shown FIG. **5**G, the outer surfaces of signal coupler **506**, containers **502**, and **504** may be uncoated, or otherwise coated with an electromagnetically translucent or substantially transparent material. Signal coupler **506** may include protrusion structures **560** and **562** to engage with, respectively, surfaces **509** and **511** of the respective containers **502** and **504**, and to function as waveguides. Coupler **506**, together with containers **502** and **504**, can be enclosed within container enclosure **508** that has internal surfaces coated with electromagnetically reflective material (e.g., metallized).

(39) The width of signal coupler **506** (labelled “w”) is selected to allow the EM signal to propagate from along the width to along the length (labelled “1”) after entering through opening **550**, and to propagate from along the length to along the width to exit through opening **552**. The dimensions of signal coupler **506** (e.g., length, width, and height) may depend on the dielectric constant(s) of the material(s) of signal coupler **506** (which may include a sealed container including a gas such as air). The dimensions and the dielectric constant(s) of signal coupler **506** may define the impedance of signal coupler **506**. In some examples, signal coupler **506** may be configured (based on selection of dimensions and/or material) to have an impedance that matches with the containers **502** and **504** (and the impedance of container enclosure **508** if there is air gap between the container and signal coupler) to minimize reflection of the EM signal as the signal propagate from container **502** to coupler **506** and from coupler **506** to container **504**. The length and width can be selected to enable a specific propagating mode in signal coupler **506**. In some examples, the dimensions of coupler **506** can be determined using a 3D electromagnetic simulation tool.

(40) In some examples, signal coupler **506** may be integrally formed as part of container enclosure **508**. In some examples, container enclosure **508** may have a cavity configured to receive signal

coupler **506**, in which an interior surface of the cavity or an exterior surface of signal coupler **506** is at least partially coated with the electromagnetically reflective material. In some examples, signal coupler **506** is coupled between containers **502**, **504**.

(41) FIG. **5**D is an angled view of a portion of PCB **514**. A transmitter (TX) antenna **515** is electrically coupled to transmitter circuitry **516** and a receiver (RX) antenna **517** is electrically coupled to receiver circuitry **518**. Antennas **515**, **517** may be similar in material respects to antennas **104**, **106**, respectively, of FIG. **1**. Circuitry **516**, **518** may be included within circuitry **108** of FIG. **1**.

(42) In some examples, antennas **515**, **517** can include flat metal layers that are on a single plane, which plane can be the plane of PCB on which circuitry **516**, **518** is mounted, such that antennas **515**, **516** can be printed on PCB **514** and electrically coupled to respective circuitry **516**, **517** via wiring printed on PCB **514**. The millimeter electromagnetic waves used to interrogate the dipolar gas contained in containers **502**, **504** can be launched directly from the PCB **514** to which container enclosure **508** is coupled. Circuitry **516**, **518** can be encapsulated over the PCB **514** with a molded enclosure. In some examples, PCB **514** can measure about 5 mm by 5 mm in length and width. However, PCB **514** can have any suitable dimensions.

(43) In some examples, PCB **514** can be electrically and mechanically coupled to a larger system board (not explicitly shown). For example, a larger system board can be a motherboard of a computer system or main system board of a mobile device, such as a smartphone. PCB **514** can be electrically and mechanically coupled to a larger system board by bump bonds, for example, through which output signals can be provided from the quantum transition frequency detector **500** to the larger system board, and/or input signals can be provided to the quantum transition frequency detector system **500** from the larger system board.

(44) Container enclosure **508** also has cavities forming (or accommodating) multiple signal couplers **510**, **512**. Signal coupler **510** is coupled between surface **532** of container **502** and antenna **515**, and signal coupler **512** is coupled between surface **534** of container **504** and antenna **517**. Surfaces **532** and **534** can be parallel with the axis of extension of containers **502** and **504** (e.g., the x-y plane) and PCB **514**. Signal couplers **510**, **512** can support vertical launch, where EM signal travel vertically (e.g., along the z-axis) between antenna **515** and container **502** and between antenna **517** and container **504**. In some examples, signal couplers **510**, **512** are each a hollow cavity interiorly coated with an electromagnetically reflective material (e.g., metallized), and with electromagnetically translucent or substantially transparent window regions (e.g., window **310**) located at the top and bottom thereof. In some examples, signal couplers **510**, **512** may each incorporate solid dielectric material (e.g., plastic) that is enclosed within electromagnetically reflective material (e.g., metallized), with electromagnetically translucent or substantially transparent window regions (e.g., window **310**) located at the top and bottom thereof. In some examples, signal couplers **510**, **512** can also have same material and solid/hollow configuration as signal coupler **506**. Regardless of whether a hollow or solid configuration is used, including a combination thereof, signal couplers **510**, **512** can operate as waveguides by guiding the propagation of EM signals therethrough.

(45) The TX and RX antennas **515**, **517** are communicatively coupled to signal couplers **510**, **512** through respective window regions **570**, **572** of containers **502**, **504** to respectively launch into and receive from container enclosure **508** the millimeter-wave electromagnetic radiation that courses through the containers **502**, **504**. More specifically, an EM signal received from transmit circuitry **516** may propagate from TX antenna **515**, through signal coupler **510**, through container **502**, through solid dielectric signal coupler **506**, through container **504**, and through signal coupler **512** to RX antenna **517**, which electrically communicates the received signal to receive circuitry **518**.

(46) FIG. **5**E is an oblique parallel projection view of container enclosure **508**. As shown in FIG. **5**E, container enclosure **508** has internal cavities **520**, **522**, **524** configured to hold in place containers **502**, **504** and signal coupler **506**, respectively. In some examples, cavities **520**, **522**, **524**

are each interiorly coated with an electromagnetically reflective material (e.g., metallized), and with electromagnetically translucent or substantially transparent window regions over window **570** and **572**. The electromagnetically reflective material (e.g., metal) can adjoin (or is substantially in contact with) the outer surfaces of each container and coupler. In some examples, container enclosure **508** is formed by 3D printing, molding, etc. In some examples, container enclosure **508** can be formed in pieces (e.g., in two halves), metallization can be selectively applied to internal cavities **520**, **522**, **524** in a manner that leaves unmetallized the aforementioned window regions (e.g., windows regions **570**, **572**), and the internally-metallized pieces can then be sealed together.
(47) FIGS. **6**A through **6**DE show various perspective views of respective portions of an example quantum transition frequency detector **600**, similar in material respects to detector **100** of FIG. **1**. FIG. **6**A is an oblique parallel projection view of detector **600** and FIGS. **6**B and **6**C are top views and side views, respectively of the same.
(48) Detector **600** is similar in certain material respects to detector **500**, including that detector **600** incorporates at least two dipolar gas-confining containers **502**, **504** communicatively coupled together via signal coupler **506** at ends **509**, **511**, all of which are enclosed within a container enclosure **608**. In detector **600**, container **502** is angled from container **504**. In this example, containers **502**, **504** extend, together with signal coupler **506**, on the same plane within container enclosure **608**. Each container can be communicatively coupled to an antenna via a signal coupler, such as one of signal couplers **520** or **522**.
(49) FIG. **6**D is an oblique parallel projection view of container enclosure **608**, which is similar in certain material respects to container enclosure **508**. Container enclosure **608** has internal cavities **620**, **622**, **624** configured to hold containers **502**, **504** and signal coupler **506**, such that container **502** is held at an angle from container **504** (e.g., in a V-shape configuration).
(50) FIGS. **7**A through **7**E show various perspective views of respective portions of an example quantum transition frequency detector **700**, similar in material respects to detector **100** of FIG. **1**. FIG. **7**A is an oblique parallel projection view of detector **700** and FIGS. **7**B and **7**C are top views and side views, respectively of the same.
(51) Detector **700** is similar in certain material respects to detector **500**, including that detector **700** incorporates at least two dipolar gas-confining containers **702**, **704** communicatively coupled together via a signal coupler **706**, all of which are enclosed within a container enclosure **708**. Signal coupler **706** can include a solid material or a hollow sealed tube. Signal coupler **706** can be made of a dielectric material (e.g., plastic, epoxy, air, a combination thereof, etc.), a glass material, etc., and can be made of a same of a different material from containers **702** and **704**. In detector **700**, container **702** has a first side surface **703**, container **704** has a second side surface **705** facing the first surface, and signal coupler **706** has opposing end surfaces **713** and **715**. End surface **713** of signal coupler **704** faces/opposes side surface **703**, and end surface **715** of signal coupler **706** faces/opposes side surface **705**, so that containers **702**, **704**, and signal coupler **706** can form an H-shape configuration. Side surface **703** can be in physical contact with end surface **713** or can be separated by an air gap. Side surface **705** can be in physical contact with end surface **715** or can be separated by an air gap.
(52) An EM signal can propagate from transmit circuitry **516** through container **702**, side surface **703**, end surface **713**, signal coupler **706**, end surface **715**, side surface **705**, container **704**, and reach receive circuitry **518**, as indicated by dotted line **719**. The dimensions and the dielectric constant(s) of signal coupler **706** can be configured to minimize the reflection of the EM signal at side surface **703**/end surface **713** and at end surface **715** and side surface **705**. Opposing first and second side surfaces **703**, **705**, and opposing end surfaces **713**, **715**, are perpendicular to the plane of extension of containers **702**, **704**, and signal coupler **706**. For example, containers **702**, **704**, and signal coupler **706** extend along the x-y plane, and first and second side surfaces **703**, **705**, and end surfaces **713**, **715** are on the x-z plane. In this example, containers **702**, **704** are parallel to each other. Each container has a respective window region **770**/**772** communicatively coupled to an

antenna via signal couplers **710**/**712**.

(53) Also, FIG. **7**D is an oblique parallel projection view of container enclosure **708**, which is similar in certain material respects to container enclosure **708**. Container enclosure **708** has internal cavities **720**, **722**, **724** configured to hold containers **702**, **704** and signal coupler **706**, such that signal coupler **706** couples together respective opposing surfaces of containers **702**, **704** (e.g., in an H-shaped configuration). Container enclosure **708** also has cavities forming (or accommodating) multiple signal couplers **710**, **712**.

(54) FIG. **7**E shows an alternative configuration for the containers **702**, **704** used for detector **700**, in which container **702** is angled from container **704**, while signal coupler **706** is positioned between and couples together respective opposing surfaces of containers **702**, **704**. In some examples in which container **702** is angled from container **704**, signal coupler **706** may have a trapezoidal shape (e.g., as shown in FIG. **7**E) to facilitate interfacing with planar opposing surfaces of containers **702**, **704**.

(55) In some examples, the outer surfaces of signal coupler **706**, together with the outer surfaces of containers **702** and **704**, can be coated with an electromagnetically reflective material (e.g., metallized). Signal coupler **706** can include openings (similar to openings **550** and **552**) on end surfaces **703** and **705**. Container **702** can also include an opening on side surface **713** aligned with the opening on end surface **703** of signal coupler **706**, and container **704** can include an opening on side surface **715** aligned with the opening on end surface **705** of signal coupler **706**. The openings can be uncoated, or otherwise coated with an electromagnetically translucent or substantially transparent material, to allow EM signal to propagate through. In some examples, the outer surfaces of signal coupler **706**, together with the outer surfaces of containers **702** and **704**, are not coated with an electromagnetically reflective material. The internal surfaces of cavities **720**, **722**, and **724** of container enclosure **708** can be coated with an electromagnetically reflective material to keep the EM signal within containers **702**, **704**, and signal coupler **706**. The electromagnetically reflective material (e.g., metal) can adjoin (or is substantially in contact with) the outer surfaces of each container and coupler.

(56) FIGS. **8**A through **8**D show various perspective views of another example arrangement of dipolar gas containers and signal coupler. Referring to FIGS. **8**A through **8**D, a quantum transition frequency detector **800** includes containers **802**, **804**, in which a first portion **802***a* of container **802** covers a second portion **804***a* of container **804**, and a signal coupler **806** is positioned between and couples together respective opposing surfaces **806** and **808** of containers **802**, **804**. In FIG. **8**A, containers **802** and **804** may extend along an x-y plane, first portion **802***a*, signal coupler **806**, and second portion **804***b* form a stack along an axis perpendicular to the extension axis/plane of containers **802** and **804** (e.g., z-axis). Signal coupler **806** can include a solid material or a hollow sealed tube. Signal coupler **806** can be made of a dielectric material (e.g., plastic, epoxy, air, a combination thereof, etc.), a glass material, etc., and can be made of a same of a different material from containers **802** and **804**. Signal coupler **806** can be in physical contact with containers **802** and **804** or can be separated by air gaps. The dimensions and the dielectric constant(s) of signal coupler **806** can be configured to minimize the reflection of the EM signal between container **802** and signal coupler **806**, and between signal coupler **806** and container **804**.

(57) FIG. **8**D is an oblique parallel projection view of a container enclosure **808**, which is similar in certain material respects to container enclosure **508**, with the exception that container enclosure **808** has internal cavities **820**, **822**, **824** configured to position portion **802***a* of container **802** to cover portion **804***a* of container **804**, and to position signal coupler **806** between portions **802***a* and **804***a*. Each container can be communicatively coupled to an antenna via a signal coupler (not shown in FIGS. **8**A-**8**D). In some examples, containers **802**, **804**, and signal coupler **806** can be coated with an electromagnetically reflective material, with interfacing windows (between container **802** and signal coupler **806**, between container **804** and signal coupler **806**, and between containers **802** and **804** and the signal couplers to the antennas) uncoated with coated with an

electromagnetically translucent or substantially transparent material. In some examples, internal surfaces of cavities **820**, **822**, and **824** can be coated with an electromagnetically reflective material. The electromagnetically reflective material (e.g., metal) can adjoin (or is substantially in contact with) the outer surfaces of each container and coupler.

(58) FIGS. **9**A through **9**D show various perspective views of another example arrangement of dipolar gas containers and signal coupler. Referring to FIGS. **9**A through **9**D, a quantum transition frequency detector **900** includes two dipolar gas-confining containers **902**, **904**, in which a first portion **902***a* of container **902** covers a second portion **902***b* of container **904** and forms a stack along a direction (e.g., z-axis) perpendicular to direction of extension of containers **902** and **904** (e.g., along the x-y plane). Also, a signal coupler **906** joins end **910** of container **902** and end **914** of container **904**. Signal coupler **906** can include a solid material or a hollow sealed tube. Signal coupler **906** can be made of a dielectric material (e.g., plastic, epoxy, air, a combination thereof, etc.), a glass material, etc., and can be made of a same of a different material from containers **902** and **904**. Signal coupler **906** can have similar features and structures as signal **506**, such as shown in FIG. **5**F and FIG. **5**G. Signal coupler **806** can be in physical contact with containers **902** and **904** or can be separated by air gaps. The dimensions and the dielectric constant(s) of signal coupler **906** can be configured to minimize the reflection of the EM signal between container **902** and signal coupler **906**, and between signal coupler **906** and container **904**.

(59) FIG. **9**D is an oblique parallel projection view of a container enclosure **908**, which is similar in certain material respects to container enclosure **508**, where container enclosure **908** has internal cavities **920**, **922**, **924** configured to position a first portion of container **902** on a second portion of container **904**, and to position signal coupler **906** proximate to and to overlap respective ends of containers **902**, **904**. Each container can be communicatively coupled to an antenna via a signal coupler (not shown in FIGS. **9**A-**9**D).

(60) FIGS. **10**A and **10**B show an oblique parallel projection and side views, respectively, of a portion of an example quantum transition frequency detector **1000** with shading representative of an electric field that is perpendicular to the direction of propagation through a rectangular dipolar gas-confining container **1002** (e.g., a TE10 mode, where "TE" refers to transverse electric). The container **1002**, a signal coupler **1010**, and a TX antenna **1015** may be similar in material respects to corresponding components **502**, **510**, and **515**, respectively, of detector **500**. In some examples, container **1002** may have a rectangular cross section having a half wavelength ($\lambda/2$) dimension across the broad side and less than a half wave length ($\lambda/2$) of the magnetic field across the narrow side. As shown in FIGS. **10**A and **10**B (and FIGS. **5**A-FIG. **9**D), the broader side of the rectangular cross section of container **1002** is parallel to top surface of the underlying TX antenna **1015**. In some examples, container **1002** may be rotated (e.g., within the range of 80 to 100 degrees, including 90 degrees) relative to what is shown in FIGS. **5**A-**10**B, where the dipolar gas-confining containers can have a width (e.g., along the y-axis) longer than a height/thickness (e.g., along the axis).

(61) FIGS. **11**A through **11**D show various views of an example quantum transition frequency detector **1100** having multiple dipolar gas-confining containers **1102**, **1104** that have a width (labelled "w" in FIG. **11**A, along the z-axis) shorter than a height (labelled "h" in FIG. **11**A, along the y-axis) and are parallel to and coplanar with each other, so that the broader side of the containers are perpendicular to (or angled from) the antennas (not shown) and PCB **514**. Frequency detector **1100** can have a similar structure and arrangement as quantum transition frequency detector **500**. Frequency detector **1100** also includes a signal coupler **1106** communicatively coupled to ends of containers **1102** and **1104**, and a container enclosure **1108** enclosing containers **1102**, **1104**, and signal coupler **1106**. Signal coupler **1106** can have similar features/structures as signal coupler **506**, such as shown in FIGS. **5**F and **5**G. Signal coupler **1106** can include a solid material or a hollow sealed tube. Signal coupler **1106** can be made of a dielectric material (e.g., plastic, epoxy, air, a combination thereof, etc.), a glass material, etc., and can be made of a same of

a different material from containers **1102** and **1104**. Signal coupler **1106** can be in physical contact with containers **1102** and **1104** or can be separated by air gaps. The dimensions and the dielectric constant(s) of signal coupler **1106** can be configured to minimize the reflection of the EM signal between container **1102** and signal coupler **1106**, and between signal coupler **1106** and container **1104**.

(62) Quantum transition frequency detector **1100** can support different transmission mode from, for example, quantum transition frequency detectors **500-1000**. For example, quantum transition frequency detectors **500-1000** may support TE10 propagation, and quantum transition frequency detector **1100** may support TE01 propagation. The narrower sides of the rectangular cross sections of containers **1102**, **1104** are parallel to the x-y plane.

(63) FIG. **11**D is an oblique parallel projection view of container enclosure **1108**. As shown in FIG. **11**D, container enclosure **1108** has internal cavities **1120**, **1122**, **1124** configured to hold in place containers **1102**, **1104** and signal coupler **1106**, respectively. In some examples, cavities **1120**, **1122**, **1124** are each interiorly coated with an electromagnetically reflective material (e.g., metallized). In some examples, the outer surfaces of containers **1102**, **1104** and signal coupler **1106** are coated with an electromagnetically reflective material (e.g., metallized), as described above. The electromagnetically reflective material (e.g., metal) can adjoin (or is substantially in contact with) the outer surfaces of each container and coupler.

(64) FIGS. **12**A through **12**D show various views of a detector **1200** having a first dipolar gas-confining container **1202** that is angled from a second dipolar gas-confining container **1204** (e.g., in a V-shape configuration), and can have a similar structure and arrangement as quantum transition frequency detector **600**. Each of containers **1202** and **1204** has a width (labelled "w" in FIG. **12**A, along the z-axis) shorter than a height (labelled "h" in FIG. **12**A, along the y-axis) and are coplanar with each other, so that the broader side of the containers are perpendicular to (or angled from) the antennas (not shown) and PCB **514**, to support a different transmission mode from detector **600**. Frequency detector **1200** also includes a signal coupler **1206** communicatively coupled to ends of containers **1202** and **1204**, and a container enclosure **1208** enclosing containers **1202**, **1204**, and signal coupler **1206**. Signal coupler **1206** can have similar features/structures as signal coupler **506**, such as shown in FIGS. **5**F and **5**G. Signal coupler **1206** can include a solid material or a hollow sealed tube. Signal coupler **1206** can be made of a dielectric material (e.g., plastic, epoxy, air, a combination thereof, etc.), a glass material, etc., and can be made of a same of a different material from containers **1202** and **1204**. Signal coupler **1206** can be in physical contact with containers **1202** and **1204** or can be separated by air gaps. The dimensions and the dielectric constant(s) of signal coupler **1206** can be configured to minimize the reflection of the EM signal between container **1202** and signal coupler **1206**, and between signal coupler **1206** and container **1204**.

(65) FIG. **12**D is an oblique parallel projection view of container enclosure **1208**. As shown in FIG. **12**D, container enclosure **1208** has internal cavities **1220**, **1222**, **1224** configured to hold in place containers **1202**, **1204** and signal coupler **1206**, respectively. In some examples, cavities **1220**, **1222**, **1224** are each interiorly coated with an electromagnetically reflective material (e.g., metallized). In some examples, the outer surfaces of containers **1202**, **1204** and signal coupler **1206** are coated with an electromagnetically reflective material (e.g., metallized), as described above. The electromagnetically reflective material (e.g., metal) can adjoin (or is substantially in contact with) the outer surfaces of each container and coupler.

(66) FIGS. **13**A through **13**E show various perspective views of respective portions of an example quantum transition frequency detector **1300**, similar in material respects to detector **100** of FIG. **1**. FIG. **13**A is an oblique parallel projection view of detector **1300** and FIGS. **13**B and **13**C are top views and side views, respectively of the same. Detector **1300** incorporates at least four dipolar gas-confining containers **1302**, **1303**, **1304**, **1305** and at least three signal couplers **1306**, **1307**, **1309**, in which signal coupler **1306** communicatively couples together containers **1303**, **1304**, signal coupler **1307** communicatively couples together containers **1302**, **1303**, and signal coupler

1309 communicatively couples together containers **1304**, **1305**. In this example, containers **1302**, **1304** are parallel to each other and are angled from containers **1303**, **1305**, respectively. Containers **1303**, **1305** are parallel to each other. In this example, an end of container **1303** is on an end of container **1302** and an end of container **1304** is on an end of container **1305**. Containers **1302**, **1305** can be enclosed within a first level of container enclosure **1308** and containers **1303**, **1304** can be enclosed within a second level of container enclosure, in which the first and second levels of container enclosure **1308** are parallel to each other and the second level is on the first level. Collectively, the arrangement of containers **1302**, **1303**, **1304**, **1305** can be deemed W-shaped or M-shaped, depending on perspective.

(67) In some examples, the intercoupling of containers **1303**, **1304** and signal coupler **1306** may be similar what is described herein with reference to containers **620**, **604** and signal coupler **606**; and the intercoupling of containers **1302**, **1303**, and signal coupler **1307** may be similar to what is described herein with reference to containers **902**, **904** and signal coupler **906**. In some examples, signal coupler **1307** may be positioned between opposing faces of containers **1302**, **1303**, such that signal coupler **1307** communicatively couples container **1302** to container **1303** in a manner similar to what is described herein with reference to containers **802**, **804** and signal coupler **806**.

(68) FIG. **13**D is an oblique parallel projection view of container enclosure **1308**, which has internal cavities **1320**, **1322**, **1324**, **1326** configured to hold containers **1302**, **1303**, **1304**, **1305**, respectively, and internal cavities **1321**, **1323**, **1325** configured to hold solid dielectric signal couplers **1307**, **1306**, **1309** and signal coupler **706**, respectively. In some examples, container enclosure **1308** is interiorly coated with an electromagnetically reflective material (e.g., metallized), such that when containers **1302**, **1303**, **1304**, **1305** are seated in container enclosure **1308**, where the material adjoins (or is substantially in contact with) the outer surfaces of each container **1302**, **1303**, **1304**, **1305** and each signal coupler **1306**, **1307**, **1309**.

(69) FIG. **13**E is an oblique parallel projection view of an alternative container enclosure **1350**, which has internal cavities configured to hold containers having a rectangular cross section, in which the containers are oriented within container enclosure **1350** such that the narrower sides are parallel to the x-y plane shown to support a different mode of transmission, as described in FIGS. **11** and **12**. Container enclosure **1350** may be otherwise similar in material respects to container enclosure **1308**.

(70) FIG. **14** is a top view of an arrangement of an example quantum transition frequency detector **1400** having at least six overlapping dipolar gas-confining containers **1402**, **1404**, **1406**, **1408**, **1410**, **1412** and at least five signal couplers **1403**, **1405**, **1407**, **1209**, **1411**. Detector **1400** and containers **1402**, **1404**, **1406**, **1408**, **1410**, **1412** can be similar in material respects to detector **100** and container **102** of FIG. **1**, respectively. Container **1402** is at an angle from container **1404** and signal coupler **1403** communicatively couples container **1402** to container **1404** in a manner similar to what is described herein with reference to containers **802**, **804** and signal coupler **806**. Container **1404** is at an angle from container **1406** and signal coupler **1405** communicatively couples container **1404** to container **1406** in a manner similar to what is described herein with reference to containers **802**, **804** and signal coupler **806**. Container **1406** is at an angle from container **1408** and signal coupler **1475** communicatively couples container **1406** to container **1408** in a manner similar to what is described herein with reference to containers **902**, **904** and signal coupler **906**. Container **1408** is at an angle from container **1410** and signal coupler **1409** communicatively couples container **1408** to container **1410** in a manner similar to what is described herein with reference to containers **802**, **804** and signal coupler **806**. Container **1410** is at an angle from container **1412** and signal coupler **1411** communicatively couples container **1410** to container **1412** in a manner similar to what is described herein with reference to containers **802**, **804** and signal coupler **806**.

(71) Containers **1402**, **1406**, **1408**, **1412** can be enclosed within a first level of a container enclosure (not explicit shown) and containers **1404**, **1410** can be enclosed within a second level of the same container enclosure, in which the first and second levels of the container enclosure are

parallel to each other, and the second level is on the first level. A multi-level approach may facilitate using various different methods of communicatively coupling adjacent containers together, thereby minimizing the space required to achieve a certain end-to-end length for the containers collectively. For example, when communicatively coupling together two containers within the same level (e.g., signal coupler **1407** communicatively couples container **1406** to container **1408**), a signal coupler can be used to couple together respective non-opposing surfaces of the containers, as described with reference to FIGS. **9**A through **9**D. When communicatively coupling together two containers within overlapping levels (e.g., signal coupler **1403** communicatively couples container **1402** within a first level to container **1404** within a second level on the first level), a signal coupler can be used to couple together respective opposing surfaces of the containers, as described with reference to FIGS. **8**A through **8**D. The communicative intercoupling of containers **1402**, **1404**, **1406**, **1408**, **1410**, **1412** by signal couplers **1403**, **1405**, **1407**, **1209**, **1411** may be expended further with additional containers, signal couplers or levels, thereby even further increasing the collective end-to-end length of containers within a maximum volume for the detector **1400**.

(72) FIGS. **15**A and **15**B show angled and side views, respectively, of an example quantum transition frequency detector **1500** having dipolar gas-confining containers **1502** and **1504** communicatively coupled together by a signal coupler **1504**, in which the containers are arranged perpendicular to (or angled from) PCB **514** containing transmit and receive antennas and circuitries. The illustrated detector is otherwise substantially similar in material respects to detector **500**. FIG. **15**C illustrates an example container enclosure **1508** having cavities **1520**, **1522**, and **1524** therein to hold in position the containers and signal coupler shown in FIGS. **15**A and **15**B. In some examples, container enclosure **1508** is interiorly coated with an electromagnetically reflective material (e.g., metallized), such that when containers **1502**, **1504**, and coupler **1506** are seated in container enclosure **1508**, where the material adjoins (or is substantially in contact with) the outer surfaces of containers **1502**, **1504** and signal coupler **1506**. In some examples, the outer surfaces of containers **1502**, **1504** and signal coupler **1506** can be coated with an electromagnetically reflective material, as described above.

(73) FIGS. **16**A and **16**B show angled and side views, respectively, of an example quantum transition frequency detector **1600** having two dipolar gas-confining containers **1602** and **1604** communicatively coupled together by a signal coupler **1606**, in which the containers are arranged perpendicular to PCB **514** containing transmit and receive antennas and circuitries. The illustrated detector is otherwise substantially similar in material respects to detector **600**. FIG. **16**C illustrates an example container enclosure **1608** having cavities **1620**, **1622**, and **1624** therein to hold in position the containers and signal coupler shown in FIGS. **16**A and **16**B. In some examples, container enclosure **1608** is interiorly coated with an electromagnetically reflective material (e.g., metallized), such that when containers **1602**, **1604**, and coupler **1606** are seated in container enclosure **1608**, where the material adjoins (or is substantially in contact with) the outer surfaces of containers **1602**, **1504** and signal coupler **1606**. In some examples, the outer surfaces of containers **1602**, **1604** and signal coupler **1606** can be coated with an electromagnetically reflective material, as described above.

(74) FIGS. **17**A and **17**B show angled and top views, respectively, of an example quantum transition frequency detector **1700** having two dipolar gas-confining containers **1702** and **1704** communicatively coupled together by a signal coupler **1706**, in which the containers are arranged perpendicular to PCB **514** containing transmit and receive antennas and circuitries. The illustrated detector is otherwise substantially similar in material respects to detector **700**. FIG. **17**C illustrates an example container enclosure having cavities **1720**, **1722**, and **1724** therein to hold in position the containers and signal coupler shown in FIGS. **17**A and **17**B. In some examples, container enclosure **1708** is interiorly coated with an electromagnetically reflective material (e.g., metallized), such that when containers **1702**, **1704**, and coupler **1706** are seated in container enclosure **1708**, where the

material adjoins (or is substantially in contact with) the outer surfaces of containers **1702**, **1704** and signal coupler **1706**. In some examples, the outer surfaces of containers **1702**, **1704** and signal coupler **1706** can be coated with an electromagnetically reflective material, as described above.

(75) FIGS. **18**A and **18**B illustrate additional example signal couplers between dipolar gas containers, such as dipolar gas containers **502** and **504** of FIGS. **5**A-**5**E and the TX and RX antennas. In FIGS. **18**A and **18**B, TX and RX antennas **1825**, **1827** can be Vivaldi antennas. Signal couplers **1830** and **1832** can be coplanar waveguides. Signal coupler **1830** can be coupled between a side surface **1842** of container **502** that is perpendicular to the axis of extension of container **502** (e.g., x-y plane), and signal coupler **1832** can be coupled between a side surface **1844** of container **504** that is perpendicular to the axis of extension of container **504** (e.g., x-y plane). Antennas **1825** and **1827** and signal couplers **1830** and **1832** can replace the antennas and signal couplers (between gas container and antennas) of the examples of quantum transition frequency detectors described herein.

(76) FIGS. **19** and **20** illustrate additional examples of container enclosure. In FIG. **19**, container enclosure **1900** can be an example of container enclosures **508**, **608**, **708**, **808**, **908**, **1108**, **1208**, **1308**, and **1350**, in examples where the dipolar-gas-confining containers extend parallel to PCB **514**. Also, in FIG. **20**, container enclosure **2000** can be an example of container enclosures **1508**, **1608**, and **1708**, where the dipolar gas containers extend perpendicular to (or angled from) PCB **514**. In some examples, container enclosure **1900** can be made using 3D printing. Container enclosure **1900** can be made of a mold compound (e.g., epoxy) and can be made using a molding process (e.g., injection molding). In a case where the internal cavities of the container enclosure is coated with an electromagnetic reflective layer (e.g., a metal layer), the container enclosure can be split along the axis of extension of the gas container (e.g., along the x-y plane for container enclosure **1900**, along the z-x or z-y plane for container enclosure **2000**) to expose the internal surfaces of the cavities, and a layer of metal can be coated (e.g., by spray coating, or other techniques) on the internal surfaces.

(77) Referring to FIGS. **19** and **20**, container enclosure **1900** can include fastening extension portions **1902** and **1904** for screw/pin (or other fastening mechanisms) to fasten container enclosure **1900** on PCB **514**. Also, container enclosure **1900** includes a notch portion **1906** to hug/fit an integrated circuit (IC) **1910** containing the mm-wave transmit and receive antennas and circuitries (e.g., circuitries **516** and **518**) on PCB **514**. The notch portion allows fitting container enclosure **1900** with IC **1910**, which can improve the mechanical coupling between container enclosure **1900** and PCB **514** and reduce stress on IC **910**. In some examples, a layer of insulating material can be placed between notch portion **1906** and IC **1910** to further protect/insulate IC **1910**. Referring to FIG. **20**, container enclosure **2000** can also include fastening extension portions **2002** and **2004** for screw/pin (or other fastening mechanisms), and a notch portion **2006** to hug/fit an integrated circuit (IC) **2010** containing the mm-wave transmit and receive antennas and circuitries (e.g., circuitries **516** and **518**) on PCB **514**.

(78) Herein, “or” is inclusive and not exclusive, unless expressly indicated otherwise or indicated otherwise by context. Therefore, herein, “A or B” means “A, B, or both,” unless expressly indicated otherwise or indicated otherwise by context. Moreover, “and” is both joint and several, unless expressly indicated otherwise or indicated otherwise by context. Therefore, herein, “A and B” means “A and B, jointly or severally,” unless expressly indicated otherwise or indicated otherwise by context. To aid the Patent Office, and any readers of any patent issued on this application, in interpreting the claims appended hereto, applicant notes that there is no intention that any of the appended claims invoke 35 U.S.C. § 112(f) as it exists on the date of filing hereof unless the words “means for” or “step for” are explicitly used in the claim language.

(79) In the foregoing descriptions, for purposes of explanation, numerous specific details are set forth to provide a thorough understanding of one or more examples. However, this disclosure may be practiced without some or all these specific details, as will be evident to one having ordinary

skill in the art. In other instances, well-known process steps or structures have not been described in detail in order not to unnecessarily obscure this disclosure. In addition, while the disclosure is described in conjunction with example examples, this description is not intended to limit the disclosure to the described examples. To the contrary, the description is intended to cover alternatives, modifications, and equivalents as may be included within the spirit and scope of the disclosure as defined by the appended claims.

(80) In this description, the term “couple” may cover connections, communications, or signal paths that enable a functional relationship consistent with this description. For example, if device A generates a signal to control device B to perform an action: (a) in a first example, device A is coupled to device B by direct connection; or (b) in a second example, device A is coupled to device B through intervening component C if intervening component C does not alter the functional relationship between device A and device B, such that device B is controlled by device A via the control signal generated by device A.

(81) Also, in this description, the recitation “based on” means “based at least in part on.” Therefore, if X is based on Y, then X may be a function of Y and any number of other factors.

(82) A device that is “configured to” perform a task or function may be configured (e.g., programmed and/or hardwired) at a time of manufacturing by a manufacturer to perform the function and/or may be configurable (or reconfigurable) by a user after manufacturing to perform the function and/or other additional or alternative functions. The configuring may be through firmware and/or software programming of the device, through a construction and/or layout of hardware components and interconnections of the device, or a combination thereof.

(83) As used herein, the terms “terminal,” “node,” “interconnection,” “pin,” and “lead” are used interchangeably. Unless specifically stated to the contrary, these terms are generally used to mean an interconnection between or a terminus of a device element, a circuit element, an integrated circuit, a device or other electronics or semiconductor component.

(84) A circuit or device that is described herein as including certain components may instead be adapted to be coupled to those components to form the described circuitry or device. For example, a structure described as including one or more semiconductor elements (such as transistors), one or more passive elements (such as resistors, capacitors, and/or inductors), and/or one or more sources (such as voltage and/or current sources) may instead include only the semiconductor elements within a single physical device (e.g., a semiconductor die and/or integrated circuit (IC) package) and may be adapted to be coupled to at least some of the passive elements and/or the sources to form the described structure either at a time of manufacture or after a time of manufacture, for example, by an end-user and/or a third-party.

(85) Circuits described herein are reconfigurable to include additional or different components to provide functionality at least partially similar to functionality available prior to the component replacement. Components shown as resistors, unless otherwise stated, are generally representative of any one or more elements coupled in series and/or parallel to provide an amount of impedance represented by the resistor shown. For example, a resistor or capacitor shown and described herein as a single component may instead be multiple resistors or capacitors, respectively, coupled in parallel between the same nodes. For example, a resistor or capacitor shown and described herein as a single component may instead be multiple resistors or capacitors, respectively, coupled in series between the same two nodes as the single resistor or capacitor.

(86) While certain elements of the described examples may be included in an integrated circuit and other elements may be external to the integrated circuit, in other examples, additional or fewer features may be incorporated into the integrated circuit. In addition, some or all of the features illustrated as being external to the integrated circuit may be included in the integrated circuit and/or some features illustrated as being internal to the integrated circuit may be incorporated outside of the integrated. As used herein, the term “integrated circuit” means one or more circuits that are: (i) incorporated in/over a semiconductor substrate; (ii) incorporated in a single semiconductor

package; (iii) incorporated into the same module; and/or (iv) incorporated in/on the same printed circuit board.
(87) In this description, unless otherwise stated, “about,” “approximately” or “substantially” preceding a parameter means being within +/−10 percent of that parameter or, if the parameter is zero, a reasonable range of values around zero.
(88) Modifications are possible in the described examples, and other examples are possible, within the scope of the claims.

Claims

1. An apparatus comprising: a first gas container; a second gas container; a signal coupler configured to transmit a signal between the first and second gas containers; a container enclosure enclosing the first and second gas containers and the signal coupler; and an electromagnetic (EM) reflective coating inside the container enclosure and covering at least part of the first gas container, at least part of the second gas container, and at least part of the signal coupler.
2. The apparatus of claim 1, wherein the first gas container has a first surface, the second gas container has a second surface, and the signal coupler has a third surface opposing the first and second surfaces.
3. The apparatus of claim 2, wherein the first gas container and the second gas container are parallel to each other.
4. The apparatus of claim 2, wherein the first gas container is angled from the second gas container.
5. The apparatus of claim 1, wherein the first gas container has a first surface, the second gas container has a second surface opposing the first surface, the signal coupler has opposing third and fourth surfaces, the third surface opposing the first surface and the fourth surface opposing the second surface.
6. The apparatus of claim 5, wherein the first gas container and the second gas container are parallel to each other.
7. The apparatus of claim 5, wherein the first gas container is angled from the second gas container.
8. The apparatus of claim 1, wherein a first portion of the first gas container is one a second portion of the second gas container; and wherein the signal coupler is between the first and second portions.
9. The apparatus of claim 1, wherein the signal coupler is a first signal coupler, and the apparatus further comprises: a third gas container; a fourth gas container enclosing a fourth dipolar gas; a second signal coupler configured to transmit a signal between the second gas container and the third gas container; and a third signal coupler configured to transmit a signal between the third gas container and the fourth gas container.
10. The apparatus of claim 9, wherein the first gas container is angled from the second gas container, the second gas container is angled from the third gas container, and the third gas container is angled from the fourth gas container.
11. The apparatus of claim 1, wherein each of the first and second gas container is configured to store a dipolar gas or a dipolar vapor.
12. The apparatus of claim 1, wherein the signal coupler includes a solid material or a cavity.
13. A system comprising: a substrate including a transmitter and a receiver; a first gas container and configured to receive a first signal from the transmitter; a second gas container and configured to transmit a second signal to the receiver; a signal coupler configured to transmit a third signal between the first and second gas containers; a container enclosure enclosing the first and second gas containers and the signal coupler; and an electromagnetic (EM) reflective coating inside the container enclosure and covering at least part of the first gas container, at least part of the second gas container, and at least part of the signal coupler.
14. The system of claim 13, wherein the first and second gas containers are parallel to a surface of

the substrate.
15. The system of claim 13, wherein the first and second gas containers are perpendicular to a surface of the substrate.
16. The system of claim 13, wherein the container enclosure has a first opening in the EM reflective coating at a first end of the first gas container and has a second opening in the EM reflective coating at a second end of the second gas container, wherein the first gas container is configured to receive the first signal via the first opening, and the second gas container is configured to transmit the second signal via the second opening.
17. The system of claim 13, wherein the EM reflective coating is on outer surfaces of the first and second gas container and the signal coupler.
18. The system of claim 13, wherein the first gas container has a first end surface, the second gas container has a second end surface, and the signal coupler has a coupler surface facing the first and second end surfaces.
19. The system of claim 13, wherein each of the first and second gas containers is configured to store a dipolar gas or a dipolar vapor, and each of the first and second signals has a frequency at a quantum transition frequency of the dipolar gas or the dipolar vapor.
20. The system of claim 13, wherein the first and second gas containers are parallel to each other.
21. The system of claim 13, wherein the first gas container is angled from the second gas container.
22. The system of claim 13, wherein the first gas container has a first surface, the second gas container has a second surface opposing the first surface, and the signal coupler has opposing third and fourth surfaces, the third surface opposing the first surface and the fourth surface opposing the second surface.
23. The system of claim 13, wherein a first portion of the first gas container is on a second portion of the second gas container; and wherein the signal coupler is coupled between the first and second portions.
24. The system of claim 13, wherein the container enclosure includes fastening extension portions coupled to the substrate.
25. The system of claim 13, wherein the container enclosure includes a notch portion to hug an integrated circuit on the substrate.
26. The system of claim 13, wherein the signal coupler includes a solid material or a cavity.