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(54) **MULTI-FUNCTIONAL FIBER OPTIC FUEL SENSOR SYSTEM HAVING A PHOTONIC MEMBRANE**

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See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,994,682 A   2/1991 Woodside
5,026,984 A   6/1991 Gerdt
(Continued)

FOREIGN PATENT DOCUMENTS

EM   1189039 A1   3/2002

OTHER PUBLICATIONS

Qingxu Yu et al., "Pressure sensor based on the fiber-optic extrinsic Fabry-Perot interferometer," Photonic Sensors, vol. 1, No. 1, Nov. 22, 2010, pp. 72-83.
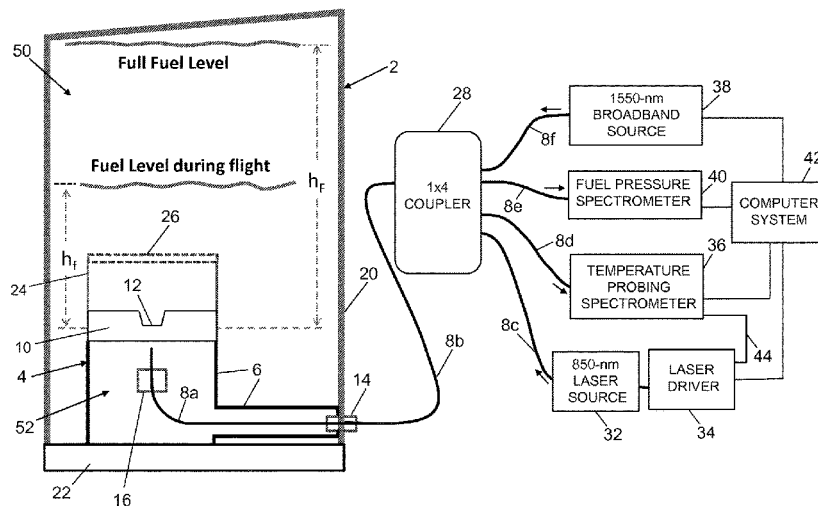(Continued)

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(57) **ABSTRACT**

A fuel sensing system utilizes a fiber optic sensor comprising a membrane made of a direct band gap semiconductor material (such as gallium arsenide) that forms an optical cavity with an optical fiber inside a hermetically sealed sensor package located at the bottom of a fuel tank. The optical fiber inside the fuel tank is not exposed to the fuel. The optical cavity formed by the bottom surface of the membrane and the surface of the distal end of the internal optical fiber is capable of behaving as a Fabry-Pérot interferometer. Multiple light sources operating at different wavelengths and multiple spectrometers can be coupled to the confronting surface of the membrane via the optical fiber inside the fuel tank, a hermetically sealed fiber optic connector that passes through the wall of the fuel tank, and a fiber optic coupler located outside the fuel tank.

19 Claims, 6 Drawing Sheets

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(56) **References Cited**

U.S. PATENT DOCUMENTS

5,072,617	A	12/1991	Weiss	
5,763,769	A *	6/1998	Kluzner	G01L 23/221
				73/114.09
6,125,218	A	3/2000	Humphrey	
6,543,294	B2 *	4/2003	Stamps	F16F 9/3264
				73/709
6,687,643	B1 *	2/2004	Cason, Jr.	G01F 23/164
				361/283.4
6,775,986	B2 *	8/2004	Ganz	F01D 17/085
				60/39.281
7,385,692	B1	6/2008	Nguyen	
2002/0050170	A1 *	5/2002	Petrovic	G01L 19/0069
				73/715
2003/0142301	A1 *	7/2003	Coleman	G01N 21/65
				356/301
2005/0041905	A1 *	2/2005	Lagakos	G01L 7/086
				385/12
2007/0129902	A1 *	6/2007	Orbell	B64D 37/02
				702/55
2007/0165238	A1 *	7/2007	Boyd	G01L 1/242
				356/478
2007/0187552	A1 *	8/2007	Tichborne	B64D 37/02
				244/135 R
2007/0272026	A1 *	11/2007	Toy	G01L 9/0079
				73/724
2008/0075404	A1 *	3/2008	Chin	G01H 9/004
				385/12
2013/0083314	A1 *	4/2013	Lambourne	G01D 5/266
				356/72
2013/0100439	A1 *	4/2013	Yu	G01N 21/255
				356/73
2013/0206760	A1 *	8/2013	Susko	G01D 11/245
				220/88.3

OTHER PUBLICATIONS

Khotiaintsev et al., "Novel Fiber-Optical Refractometric Sensor Employing Hemispherically-Shaped Detection Element", Optical Engineering, vol. 41, No. 4 (2002).

Zhao et al., "Novel light-leaking optical fiber liquid level sensor for aircraft fuel gauging", Optical Engineering, vol. 52, No. 1 (2013).
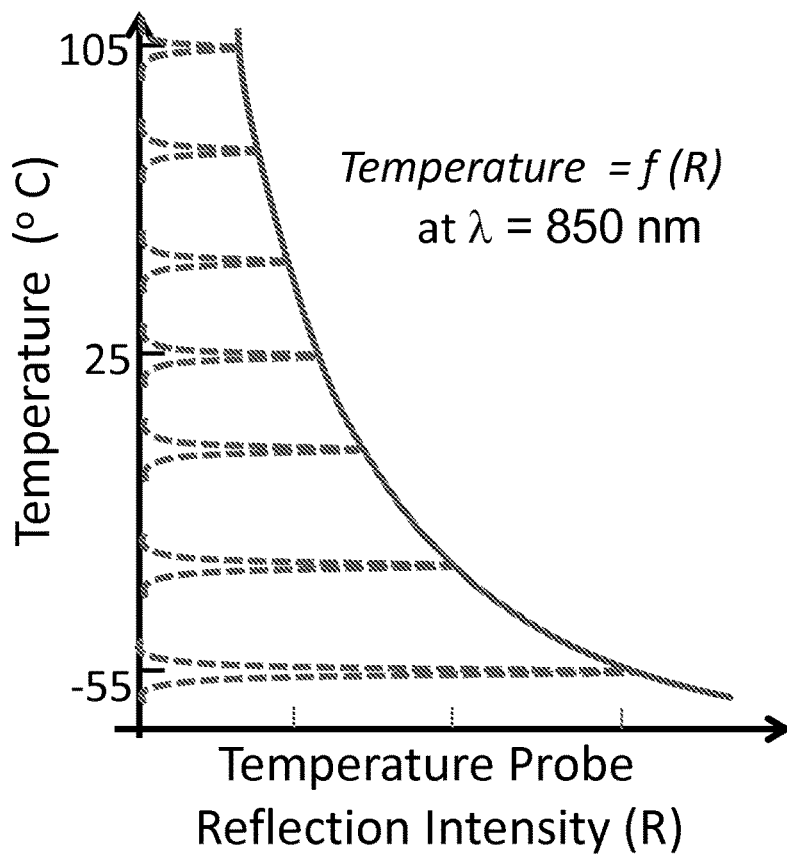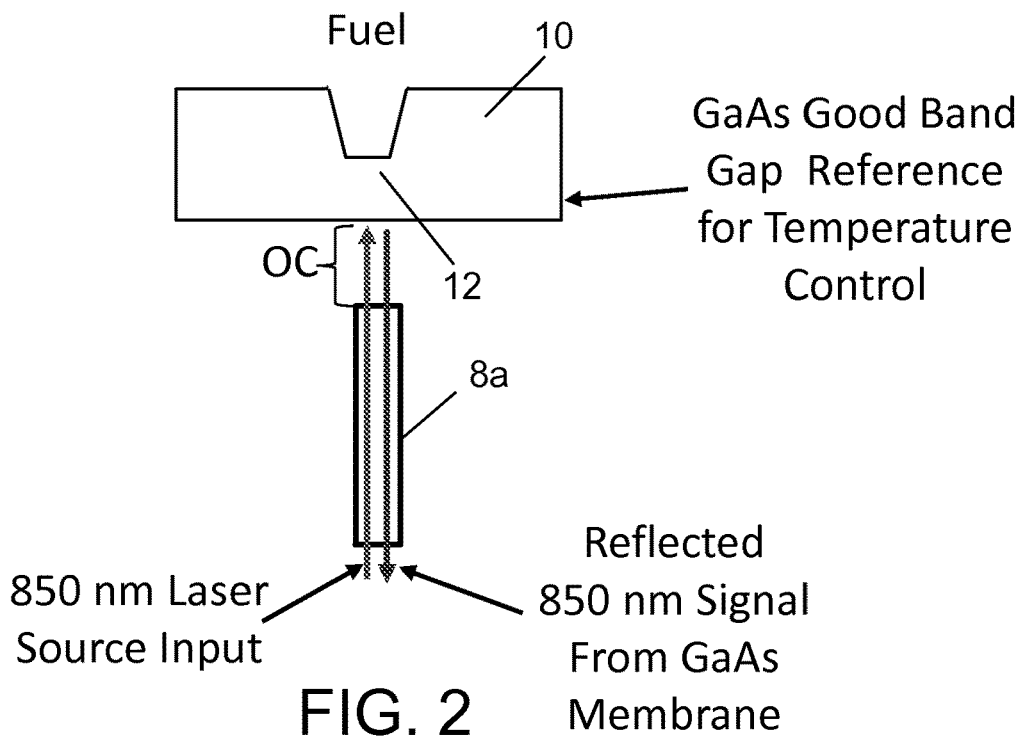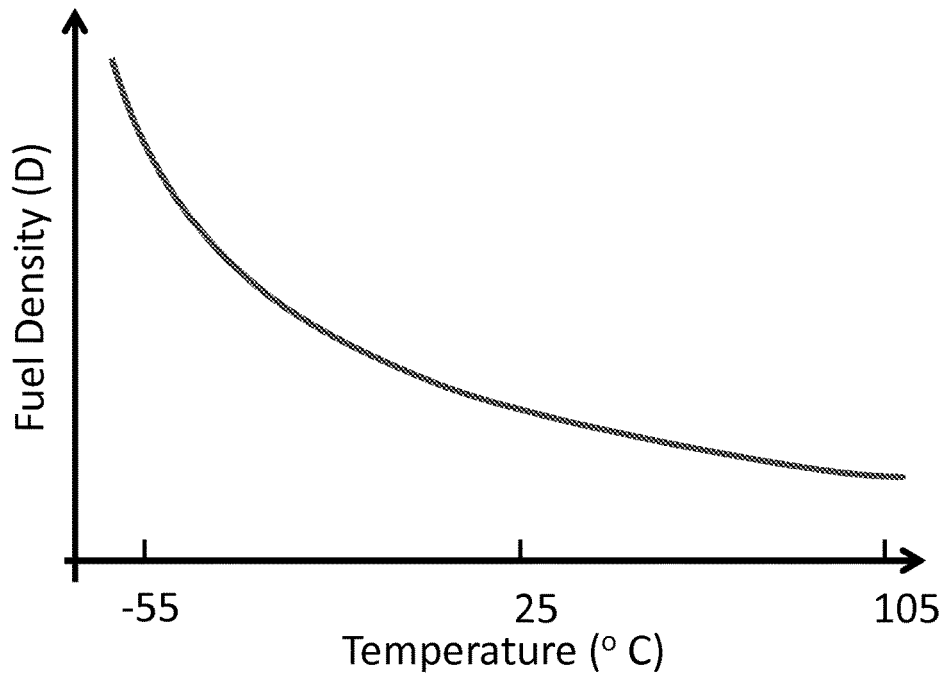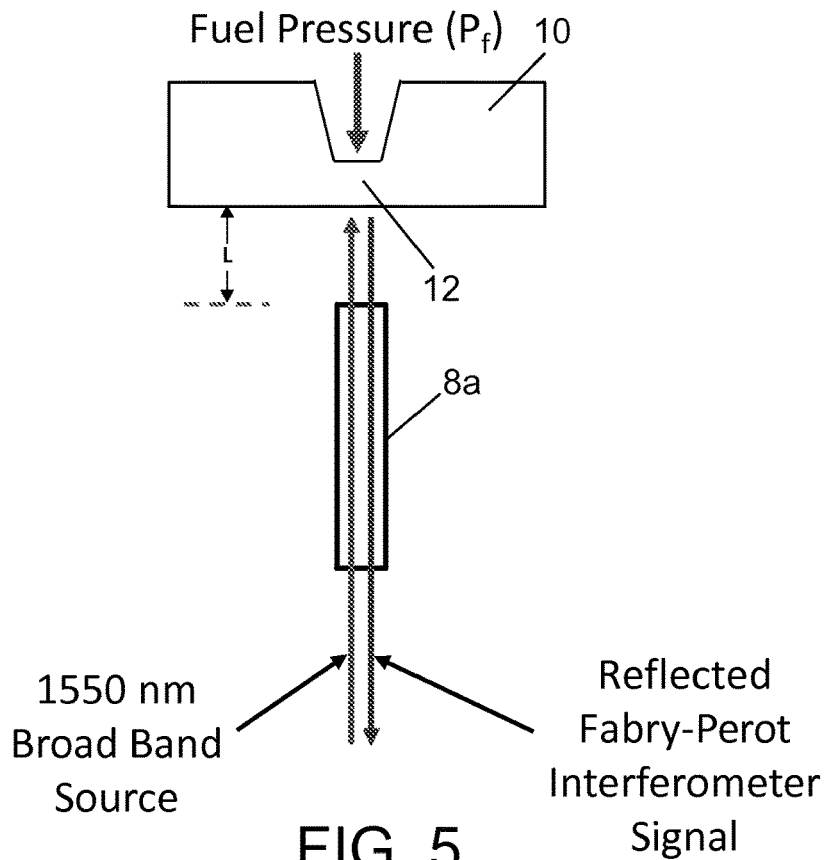
* cited by examiner

FIG. 1

Fuel   10

GaAs Good Band
Gap Reference
for Temperature
Control

OC

12

8a

850 nm Laser
Source Input

Reflected
850 nm Signal
From GaAs
Membrane

FIG. 2

Temperature = $f(R)$
at λ = 850 nm

105

25

-55

Temperature (°C)

Temperature Probe
Reflection Intensity (R)

FIG. 3

FIG. 4

FIG. 5

1550 nm Fuel Level Probing
(Broad Band) Source Spectrum

Pressure Sensing
Reflection Intensity

Free Spectral Range

$\Delta\lambda$

Reflected Signal
From GaAs
Membrane

1530   1550   1570

Wavelength (nm)

FIG. 6

Fuel   10

GaAs is Transparent
to 1060 nm
Optical Source

12

8a

1060 nm Laser
Source Input

Raman
Scattering Signal
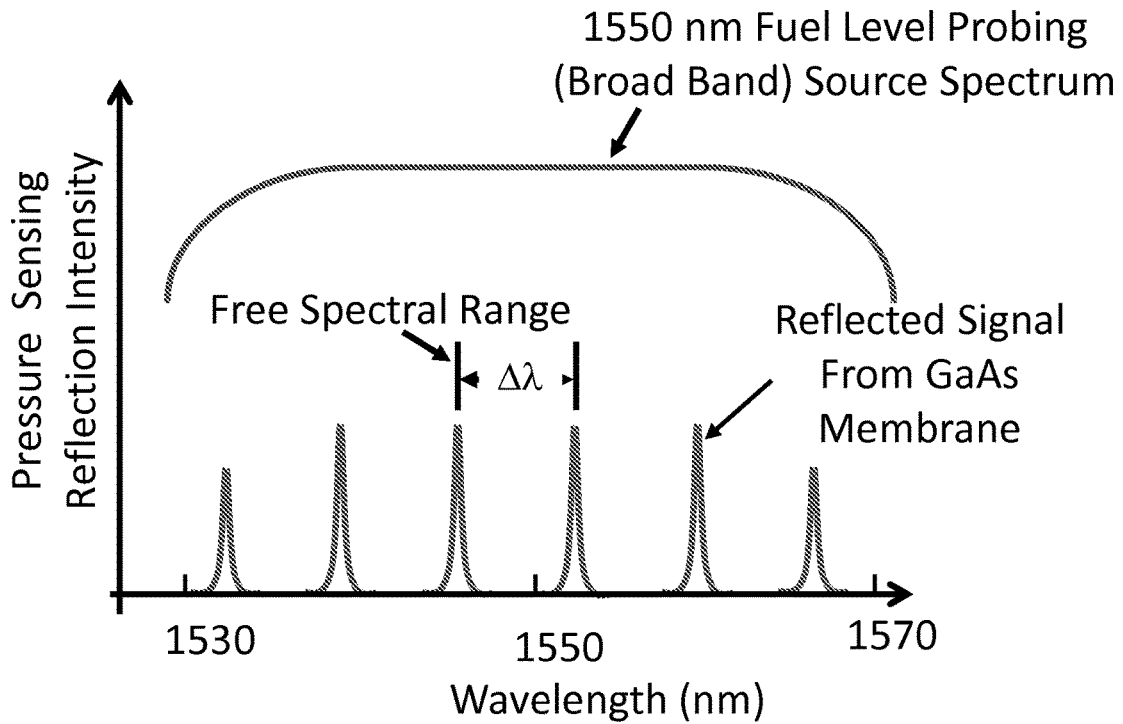from Fuel above the
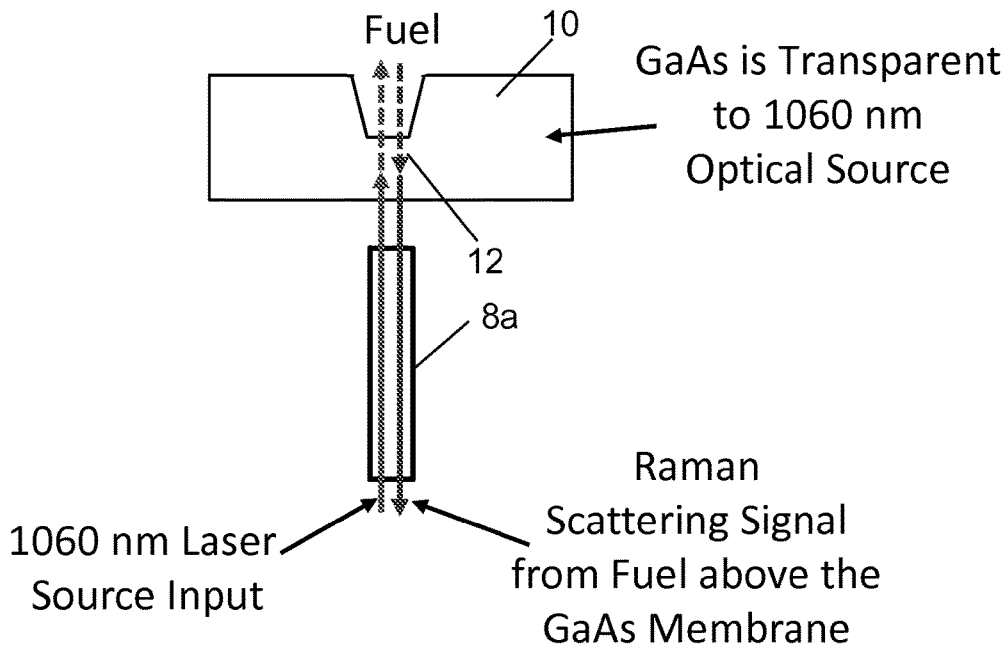GaAs Membrane

FIG. 8

FIG. 7

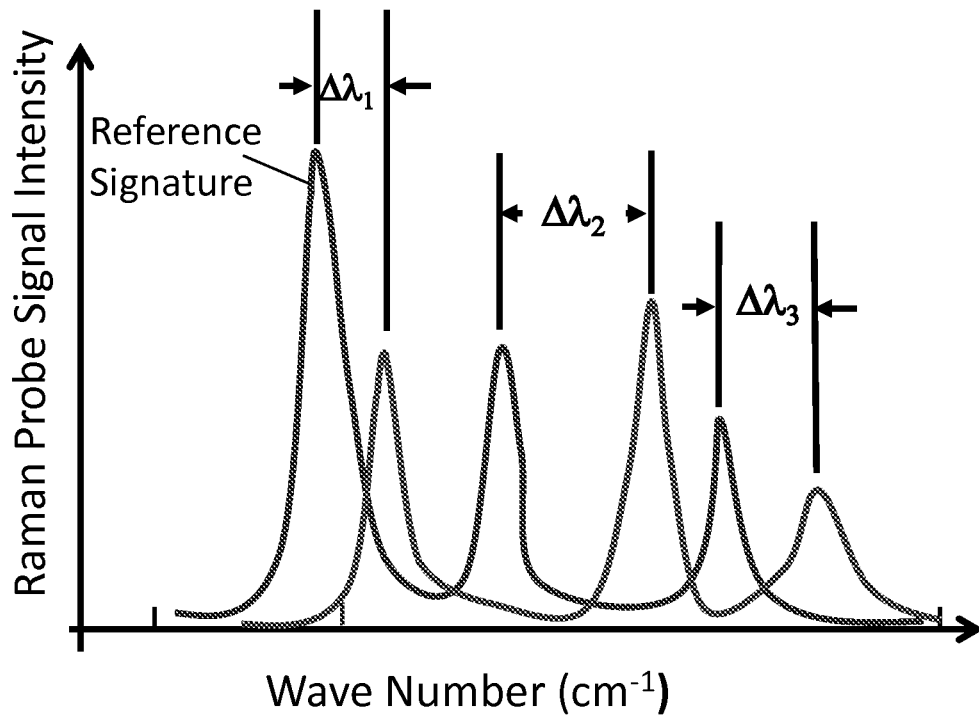*Fuel Composition = f (Peak wavelength shift)*

FIG. 9

MULTI-FUNCTIONAL FIBER OPTIC FUEL SENSOR SYSTEM HAVING A PHOTONIC MEMBRANE

BACKGROUND

This disclosure generally relates to systems and methods for measuring a level of liquid in a reservoir, such as a storage tank or other container. More particularly, this disclosure relates to systems and methods for liquid level measurement using an optical sensor.

A need to continuously measure the level of a liquid exists in many commercial and military applications. For example, liquid-level sensors are commonly used in the fuel tanks of aircraft, automobiles and trucks. Liquid-level sensors are also used to monitor liquid levels within storage tanks used for fuel dispensing, wastewater treatment, chemical storage, food processing, etc.

Many transducers for measuring liquid level employ electricity. The electrical output of such transducers changes in response to a change in the liquid level being measured, and is typically in the form of a change in resistance, capacitance, current flow, magnetic field, frequency and so on. These types of transducers may include variable capacitors or resistors, optical components, Hall Effect sensors, strain gauges, ultrasonic devices and so on.

Currently most fuel sensors on aircraft use electricity. For example, existing electrical capacitance sensors require electrical wiring inside the tank, which in turn requires complex installations and protection measures to preclude a safety issue under certain electrical fault conditions. This electrical wiring requires careful shielding, bonding and grounding to minimize stray capacitance and further requires periodic maintenance to ensure electrical contact integrity.

For new airplanes with large fuel tanks incorporated in composite wings, the numbers of fuel sensors is large. Using electrical fuel sensors adds more weight to the airplane not only because of the electrical sensor and electrical cable weight, but also because the metal standoffs and harnesses that support the electrical cables and sensors inside the fuel tank add more weight. And more importantly, with large fuel tanks in composite wings, electromagnetic interference (EMI) and lightning can be a challenge for electrical fuel sensors.

Other approaches involve the use of fiber optic fuel sensors which require one or two fiber optic sensing elements to be placed in the fuel. Any change in fuel density causes changes in the index of refraction of the fuel. This in turn causes a change in the intensity of the light transmitted from one fiber optic sensing element to the other. The problems afflicting fiber optic fuel sensors can include fuel temperature variation, icing in the fuel, and fungus and fuel residue deposit on the fiber optic sensing elements that blocks the light transmission and renders the sensor useless over the lifetime of a commercial airplane.

Other, more complicated, optical methods have been studied. One such method connects fiber optics to a capacitance sensor and converts light to electricity to operate the capacitance sensor and then converts it back to light coming out of the sensor so there are still active electronics within the fuel tank. Some have proposed the use of light-leaking fiber for fuel level measurement but these all employ the principle of refraction and require the fiber to be in contact with the fuel to modulate the light transmission angle at the cladding layer due to the different refractive index of the fuel.

There is room for improvements in systems and methods for sensing properties (such as level, density, temperature and chemical composition) of liquid fuel in a fuel tank.

SUMMARY

The subject matter disclosed herein is directed in part to the design of fiber optic fuel sensor systems that eliminate complex electrical wirings inside fuel tanks for measuring fuel temperature, fuel density, fuel level and fuel chemical composition, while maintaining accuracy and reducing cost, weight and volume as compared to existing electrical sensors. The fiber optic fuel sensor systems disclosed in detail below incorporate fuel sensors which do not need to be in contact with the fuel.

In accordance with one embodiment, the fuel sensing system utilizes a fiber optic sensor comprising a membrane made of a direct band gap semiconductor material (such as gallium arsenide) that forms an optical cavity with an optical fiber inside a hermetically sealed sensor package located at the bottom of the fuel tank. The optical fiber inside the fuel tank is not exposed to (i.e., not in contact with) the fuel. The optical cavity formed by the bottom surface of the membrane and the surface of the distal end of the internal optical fiber is capable of behaving as a Fabry-Pérot interferometer. Multiple light sources operating at different wavelengths and multiple spectrometers can be coupled to the confronting surface of the membrane via the optical fiber inside the fuel tank, a hermetically sealed fiber optic connector that passes through the wall of the fuel tank, and a fiber optic coupler located outside the fuel tank.

For the purpose of illustration, a fuel sensing system that has a membrane made of gallium arsenide (GaAs) will be described in detail below. However, other direct band gap semiconductor materials can be used, such as indium phosphide (InP).

In an embodiment that has a GaAs membrane, the temperature of the fuel can be continuously measured as a function of the reflectivity of the GaAs membrane when light from an 850-nm laser source impinges on the bottom surface of the membrane. The fuel density can be derived from the measured temperature. With fuel density derived, the fuel pressure being exerted on the top surface of the GaAs membrane can be derived from the Fabry-Pérot resonator cavity reflection spectrum of the GaAs membrane using an input broadband source preferably having a wavelength of about 1550 nm. Using the fuel density and fuel pressure, the fuel level of the tank can be measured at any time, i.e., during flight, before flight, and after flight of the airplane. Furthermore, when light from a 1060-nm laser source impinges onto the GaAs membrane, a Raman spectrometer can be used to analyze the optical scattering signal from the fuel, enabling the fuel chemical composition to be monitored continuously.

The system disclosed herein avoids the problems associated with use of electrical sensors because the fiber optic sensor has no electrical wiring inside the fuel tank, and because the optical fiber is in a hermetic package which is not exposed to the fuel, thereby eliminating light blockage due to fuel residue, fungus, fuel dirt deposit and contamination. The fiber optic sensor disclosed herein performs multiple sensing functions, which reduces the weight, size, power and cost of the system, because the number of sensors required for the fuel sensing function is reduced, This multi-functional fiber optic sensor also eliminates the light-

ning and EMI problems because no electrical wiring or electrical power is required to apply to the sensor placed inside the fuel tank.

One aspect of the subject matter disclosed in detail below is a system for storing a liquid, comprising: a reservoir comprising an enclosure; a chamber-defining structure disposed inside the enclosure that divides an internal volume of the enclosure into a storage compartment and a chamber which are hermetically sealed from each other, the chamber-defining structure comprising a membrane having a top surface that partly defines the storage compartment and a bottom surface that partly defines the chamber, and a housing that supports the membrane and partly defines the chamber; and an optical fiber having a length disposed inside the chamber, the length of optical fiber having a distal end with a surface that confronts the bottom surface of the membrane with a gap therebetween, wherein the membrane is made of a semiconductor material that has a direct band gap. Preferably, membrane is sufficiently thin that the membrane is capable of flexing upward or downward when a magnitude of a pressure being exerted on its top surface changes. In preferred embodiments, the membrane has a thickness in a range of 0.01 mm to 0.5 mm, while the semiconductor material is gallium arsenide or indium phosphide. In one embodiment, the gap has a dimension such that the bottom surface of the membrane and a confronting surface of the distal end of the optical fiber form a Fabry-Pérot resonator cavity. The disclosed system has multiple applications. For example, the reservoir may be incorporated in a wing of an aircraft.

The system described in the preceding paragraph may further comprise: an optical source for outputting light; a spectrometer for converting received light into an electrical signal representing a characteristic of the received light; an optical coupler which optically couples the optical source and the spectrometer to the optical fiber; and a computer system programmed to compute a value of a parameter of liquid contained in the reservoir based on electrical signals received from the spectrometer. The parameter may be selected from the following group: a temperature of the liquid, a pressure of the liquid, a level of the liquid, and a chemical composition of the liquid.

Another aspect of the disclosed subject matter is a system for storing a liquid, comprising: a storage tank; a hermetically sealed package disposed inside the storage tank; the hermetically sealed package comprising a membrane and a length of optical fiber, wherein the membrane has a top surface that is part of an exterior surface of the hermetically sealed package and a bottom surface that is part of an interior surface of the hermetically sealed package, wherein the membrane is made of a semiconductor material that has a direct band gap, and the length of optical fiber has a distal end with a surface that confronts the bottom surface of the membrane with a gap therebetween; a first optical source for outputting light; a first spectrometer for converting received light into an electrical signal representing a characteristic of the received light; and an optical fiber network which optically couples the optical source and the spectrometer to the length of optical fiber, the optical fiber network comprising an optical coupler. In some embodiments, the first optical source is a laser source, the first spectrometer is a temperature probing spectrometer, and the system further comprises a computer system programmed to determine a temperature of liquid contained in the storage tank based on electrical signals received from the temperature probing spectrometer following output of light from the laser source. In other embodiments, the first optical source is a broadband

light source, the first spectrometer is a pressure sensing spectrometer, and the system further comprises a computer system programmed to determine a pressure of liquid contained in the storage tank based on electrical signals received from the pressure sensing spectrometer following output of light from the broadband light source. In yet other embodiments, the first optical source is a laser source, the first spectrometer is a Raman spectrometer, and the system further comprises a computer system programmed to determine a chemical composition of liquid contained in the storage tank based on electrical signals received from the Raman spectrometer following output of light from the laser source. In accordance with further embodiments, the system further comprises: a second optical source for outputting light, the second optical source being optically coupled to the length of optical fiber by the optical fiber network; a second spectrometer for converting received light into an electrical signal representing a characteristic of the received light, the second spectrometer being optically coupled to the length of optical fiber by the optical fiber network; and a computer system programmed to compute a level of the liquid contained in the reservoir based on electrical signals received from the first and second spectrometers. In accordance with one embodiment, the first optical source is a laser source, the second optical source is a broadband source, and the computer system is programmed to perform the following operations: determine a temperature of the liquid contained in the storage tank based on electrical signals received from the first spectrometer; calculate a density of the liquid contained in the storage tank based on the determined temperature; determine a pressure of the liquid contained in the storage tank based on electrical signals received from the second spectrometer; and calculate a level of the liquid contained in the storage tank based on the calculated density and the determined pressure.

In accordance with a further aspect, a method for determining a characteristic of liquid stored in a storage tank is provided which comprises: placing a hermetically sealed package inside the storage tank, the hermetically sealed package comprising a membrane and a length of optical fiber, wherein the membrane has a top surface that is part of an exterior surface of the hermetically sealed package and a bottom surface that is part of an interior surface of the hermetically sealed package, wherein the membrane is made of a semiconductor material that has a direct band gap, and the length of optical fiber has a distal end with a surface that confronts the bottom surface of the membrane with a gap therebetween; emitting light from a first optical source that enters a proximal end of the optical fiber, exits the distal end of the optical fiber, and impinges on the bottom surface of the membrane; guiding light from the membrane that enters the distal end of the optical fiber toward a proximal end of the optical fiber after the light has been emitted by the first optical source; measuring a first property of the light that exited the proximal end of the optical fiber using a first spectrometer after the light has been emitted by the first optical source; and processing electronic data output by the first spectrometer to determine a first characteristic of liquid disposed inside the storage tank and on top of the membrane. The foregoing method may further comprise: emitting light from a second optical source that enters a proximal end of the optical fiber, exits the distal end of the optical fiber, and impinges on the bottom surface of the membrane; guiding light from the membrane that enters the distal end of the optical fiber toward a proximal end of the optical fiber after the light has been emitted by the second optical source; measuring a second property of the light that exited the

proximal end of the optical fiber using a second spectrometer after the light has been emitted by the second optical source; and processing electronic data output by the second spectrometer to determine a second characteristic of liquid disposed inside the storage tank and on top of the membrane. In one embodiment, the first characteristic is temperature, the second characteristic is pressure, and the method further comprises: calculating a density of the liquid contained in the storage tank based on the determined temperature; and calculating a level of the liquid contained in the storage tank based on the calculated density and the determined pressure.

Other aspects of optical sensor systems suitable for use with liquid storage tanks are disclosed and claimed below.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a diagram representing components of a multi-function fiber optic fuel sensor system in accordance with one embodiment that uses a GaAs photonic membrane to measure fuel temperature, fuel density and fuel level.

FIG. **2** is a diagram demonstrating the GaAs photonic membrane fuel temperature sensing principle employed by the fiber optic fuel sensor system schematically depicted in FIG. **1**.

FIG. **3** is a graph of GaAs photonic membrane temperature (in ° C.) versus reflection intensity R for impinging light having a wavelength of 850 nm.

FIG. **4** is a graph of fuel density D versus fuel temperature (in ° C.).

FIG. **5** is a diagram demonstrating the GaAs photonic membrane fuel pressure sensing principle employed by the fiber optic fuel sensor system schematically depicted in FIG. **1**.

FIG. **6** is a graph showing the pressure sensing reflection intensity over a range of wavelengths for light signals reflected from the GaAs photonic membrane to a pressure sensing spectrometer incorporated in the fiber optic fuel sensor system schematically depicted in FIG. **1**.

FIG. **7** is a diagram representing components of a multi-function fiber optic fuel sensor system in accordance with one embodiment that uses a GaAs photonic membrane to measure fuel temperature, fuel density, fuel level and fuel chemical composition.

FIG. **8** is a diagram demonstrating the principle underlying the method of sensing the fuel chemical composition employed by the fiber optic fuel sensor system schematically depicted in FIG. **7**, which method uses a GaAs photonic membrane and the Raman technique.

FIG. **9** is a graph showing changes in signal intensity versus wave number detected by a Raman spectrometer, which changes correspondingly to indicate a change in fuel chemical composition.

Reference will hereinafter be made to the drawings in which similar elements in different drawings bear the same reference numerals.

DETAILED DESCRIPTION

Various embodiments of systems and methods for measurement of a level and other properties of liquid in a reservoir will now be described in detail for the purpose of illustration. At least some of the details disclosed below relate to optional features or aspects, which in some applications may be omitted without departing from the scope of the claims appended hereto.

The basic fuel quality sensor requirements for a fuel tank incorporated in composite wings of an aircraft are fuel temperature, fuel density and fuel level sensing. The sensing function of the sensor needs to be dynamic, which means the sensor should be able to provide these key fuel quality values on the ground or during flight, at different flight envelopes and in extreme temperature and environmental conditions. The multi-function fiber optic sensor disclosed herein is designed to meet the fuel quality sensing requirements for composite wings. The proposed fiber optic sensor eliminates the use of electrical cables and electrical power inside the fuel tank, and eliminates EMI and lightning problems for the composite fuel tank. Furthermore, it reduces the size, weight and power of the electrical sensors used in current commercial airplanes. However, the technology disclosed herein may be applied to other types of liquid reservoirs and is not limited to use in fuel tanks onboard aircraft.

FIG. **1** is a diagram representing components of a multi-function fiber optic fuel sensor system in accordance with one embodiment. The fiber optic fuel sensor of this system can be installed inside a fuel tank **2** comprising a wall **20** and a bottom **22**. This fiber optic fuel sensor system uses a GaAs photonic membrane **12** to measure the temperature, density and level of liquid fuel in the fuel tank **2**. The thin GaAs membrane **12** is formed in a central portion of a GaAs substrate **10**. Gallium arsenide is used instead of silicon because of its superior property for use in temperature sensing. The portion of substrate **10** which surrounds the membrane **12** has a thickness greater than the thickness of the membrane **12**. Preferably, the GaAs membrane has a thickness in the range of 0.01 to 0.5 mm and a diameter such that it will be sufficiently flexible when a fuel pressure is exerted on a top surface of the membrane. Preferably the GaAs membrane **12** has a generally horizontal orientation.

The GaAs substrate **10** is a component of a hermetically sealed fiber optic package **4** which can be installed in the fuel tank **2** as a pre-assembled unit. The periphery of the GaAs substrate **10** is bonded to a housing **6** that is also part of the fiber optic package **4**. The housing **6** in conjunction with the GaAs substrate **12** effectively divides the internal volume of the fuel tank **2** into a fuel storage compartment **50** (filled with fuel) and a chamber **52** (having no fuel). The GaAs substrate **12** is hermetically sealed to the housing **6** to prevent entry of fuel from the fuel storage compartment **50** to the chamber **52** through the substrate/housing interface.

Preferably at least the space above the GaAs membrane **12** is enclosed and protected by a fine mesh filter **26** that filters out large-size residue, particles or dirt from the fuel occupying the space above the GaAs membrane **12**. In the embodiment shown in FIG. **1**, the filter **26** is supported by a support wall **24** which surrounds the space above the GaAs substrate **10**. The filter support wall **24** may be attached to the periphery of the GaAs substrate **10** or may be an extension of the housing **6** which surrounds and extends above the elevation of the top surface of the GaAs substrate **10**. The filter **26** and filter support wall **24** can be incorporated in the pre-assembled fiber optic package **4** or attached after installation of the fiber optic package **4**. The filter **26** is configured to admit liquid fuel into the space above the GaAs membrane **12** and inside the support wall **24**, while excluding particulate matter from outside that space.

Still referring to FIG. **1**, the fiber optic package **4** further comprises an optical fiber **8a**, a fiber optic connector **14**, and a fiber alignment and locking pedestal **16**. The fiber optic connector **14** is fixedly seated in an opening in the housing **6**, but has a portion which projects out of the housing **6** and through an opening in the wall **20** of the fuel tank **2** when the package **4** is installed. The fiber optic connector **14** is

hermetically sealed in both the opening in the housing **6** and the opening in the wall **20** of the fuel tank **2** so that fuel cannot flow from the fuel storage compartment **50** into the chamber **52** or out of the fuel tank **2** in the area of the fiber optic connector **14**.

The fiber alignment and locking pedestal **16** is connected to the bottom of the housing **6** by a support structure not shown in FIG. **1**. This support structure may comprise a sufficiently stiff structure which connects the fiber alignment and locking pedestal **16** to a bottom of the housing **6**. The connecting structure should be sufficiently rigid that the fiber alignment and locking pedestal **16** is stable and moves as little as possible during operation of the aircraft. More specifically, the fiber alignment and locking pedestal **16** supports the distal end of the optical fiber **8a** in a manner such that a surface of that distal end confronts a bottom surface of the GaAs membrane **12** with a small gap of constant length therebetween. That small gap is referred to herein as the optical cavity and is indicated by the label "OC" in FIG. **2** and other figures.

The installation or removal of a pre-assembled unit has the advantage that the entire unit can be readily replaced or removed for repair in the event of a malfunction. However, in alternative embodiments the optical fiber **8a** and GaAs substrate **10** could be supported in the same spatial relationship using a support structure which is integrated with the fuel tank **2** so long as the support structure defines a hermetically sealed chamber in which the optical fiber is not in contact with the fuel in the fuel tank.

In the embodiment depicted in FIG. **1**, the membrane is made of gallium arsenide, which is a direct band gap material. However, other direct band gap materials can be used, such as indium phosphide (InP). A band gap is "direct" if the momentum of electrons and holes is the same in both the conduction band and the valence band, meaning that an electron can directly emit a photon without passing through an intermediate state and transferring momentum to the crystal structure.

The optical fiber **8a** (preferably multi-mode, but single-mode is acceptable) inside the hermetically sealed fiber optical package **4** is aligned with and confronts the bottom surface of the GaAs membrane **12** in the central portion of the GaAs substrate **10**. The term single-mode is meant to include optical fibers with core diameter range from 8 to 10 microns which transmit only a single optical waveguide mode in the fiber. Single-mode fibers are glass optical fibers with total diameter about 125 microns with the cladding around the core. Similarly, the term multi-mode is meant to include optical fibers with core diameters from 50 microns to 1 mm. Multi-mode fibers transmit multiple optical waveguide modes in the fiber because of their large core diameter. Multi-mode fibers can be made of glass or plastic. Glass multi-mode optical fibers have total diameters in a range from 125 to 140 microns with the cladding around the core, while plastic multi-mode fibers have core diameters in a range from 0.1 to 0.98 mm and total diameters in a range from 0.25 to 1 mm with the cladding around the core. Preferably the distal end of the optical fiber **8a** is aligned precisely with a center of the GaAs membrane **12** and attached to the fiber alignment and locking pedestal **16** using a high-reliability fiber soldering process. The proximal end of the optical fiber **8a** is optically coupled to one end of an optical fiber **8b** (disposed outside the fuel tank **2**) by the hermetic and leakproof fiber optic connector **14** inserted in an opening in the wall **20** of the fuel tank **2**.

The optical fiber **8a** inside the fuel tank **2** is optically coupled to the output side of a 1×4 fiber optic coupler **28** by

the optical fiber **8b**. The function of the 1×4 fiber optic coupler **28** is to couple the optical signal from an optical source located outside the fuel tank **2** into the optical fiber **8a** inside the fuel tank **2** and then couple the optical signal from the optical fiber **8a** into a spectrometer located outside the fuel tank **2** for analysis of the optical signal coming from the GaAs membrane **12**. On the other side, the 1×4 fiber optic coupler **28** is connected to four optical fibers **8c** through **8f**.

One pair of optical fibers **8c** and **8d** are used for heating and temperature sensing of the bottom surface of the GaAs membrane **12**. The optical fiber **8c** is connected to a laser source **32** (e.g., a laser diode) which is driven by a laser driver **34** to provide a 850-nm laser source (by way of fiber optic coupler **28**, optical fiber **8b**, fiber optic connector **14**, and optical fiber **8a**) to illuminate the bottom surface of the GaAs membrane **12**. The optical fiber **8a** inside the fiber optic package **4** couples the 850-nm optical signal to the bottom surface of the GaAs membrane **12** across the optical cavity. The optical signal representing the reflection from the bottom surface of GaAs membrane **12** (indicated by an arrow adjacent to optical fiber **8d** in FIG. **1**) is coupled by the optical fiber **8a**, fiber optic connector **14**, optical fiber **8b**, fiber optic coupler **28**, and optical fiber **8d** back to a temperature probing spectrometer **36**.

FIG. **2** is a diagram demonstrating the GaAs photonic membrane fuel temperature sensing principle employed by the fiber optic fuel sensor system schematically depicted in FIG. **1**. Gallium arsenide is a semiconductor which has a direct band gap that varies with temperature: as the temperature of the fuel decreases, the GaAs membrane band gap increases. This reduces the absorption of the 850-nm signal (indicated by an upward arrow in FIG. **2**). When the absorption is reduced, the reflection signal (indicated by a downward arrow in FIG. **2**) increases. As the fuel temperature increases, the band gap of the GaAs membrane **12** decreases. This decrease in band gap has the effect of increasing the absorption the 850-nm light signal and reducing the reflection of the 850-nm signal. The increase and decrease in the amount of reflected light is precisely detected and analyzed by the temperature probing spectrometer **36**.

FIG. **3** is a graph of GaAs photonic membrane temperature (in ° C.) versus reflection intensity R for 850-nm coherent light impinging on a GaAs membrane. Based on the data represented by the curve shown in FIG. **3**, the temperature probing spectrometer **36** measures the temperature of the fuel instantaneously and outputs electrical signals representing that fuel temperature to a computer system **42**. Since the fuel density is a well-known function of temperature as shown in FIG. **4**, the computer system **42** can process the fuel temperature information and perform the necessary calculations for determining the fuel density D instantaneously. Using the temperature measured by the temperature probing spectrometer **36**, the density of the fuel can be determined by the computer system **42** any time during flight or while the aircraft is on the ground.

After the fuel density D has been determined, the fuel level can be determined from the fuel pressure measured at the GaAs membrane **12**. Returning to FIG. **1**, the other pair of optical fibers **8e** and **8f** are used for sensing the fuel pressure being exerted on the GaAs membrane **12**. The optical fiber **8f** is connected to a broadband light source **38** which is driven to provide a spectrum of light centered at 1550 nm with a flat spectral width of about 40 nm (by way of fiber optic coupler **28**, optical fiber **8b**, fiber optic connector **14**, and optical fiber **8a**) to illuminate the bottom surface of the GaAs membrane **12**. The optical fiber **8a**

inside the fiber optic package **4** couples the 1550-nm optical signal to the bottom surface of the GaAs membrane **12** across the optical cavity. The optical signal representing the reflections of the broadband light from the bottom surface of GaAs membrane **12** (indicated by an arrow adjacent to optical fiber **8e** in FIG. **1**) is coupled by the optical fiber **8a**, fiber optic connector **14**, optical fiber **8b**, fiber optic coupler **28**, and optical fiber **8e** back to a pressure sensing spectrometer **40**.

FIG. **5** is a diagram demonstrating the GaAs photonic membrane fuel pressure sensing principle employed by the fiber optic fuel sensor system schematically depicted in FIG. **1**. The distance separating the surface of the distal end of the optical fiber **8a** and the confronting portion of the bottom surface of the GaAs membrane **12** (referred to herein as the "optical cavity length") is indicated by a variable length L in FIG. **1**. When the fuel compartment **50** (see FIG. **1**) is empty, the optical cavity length has a value L_0; in contrast, when the fuel compartment **50** has sufficient fuel that the space above the GaAs membrane **12** is at least partially occupied by fuel, then that fuel will exert a downward pressure on the flexible GaAs membrane **12**. The fuel pressure exerted on the GaAs membrane **12** causes a downward deflection of the membrane **12**, thereby reducing the optical cavity length L. Since the bottom surface of the GaAs membrane **12** and the surface of the distal end of the optical fiber **8a** form a Fabry-Pérot resonator cavity (a.k.a. a Fabry-Pérot interferometer), the change in the optical cavity length ΔL can be measured by the pressure sensing spectrometer **40** using the multiple reflections returned by from Fabry-Pérot resonator cavity.

As shown in FIG. **1**, the fuel level height is dynamically changing. Upon fuel fill-up on the ground, the full (i.e., initial) fuel level is h_F. In contrast, during flight the in-flight (i.e., current) fuel level is h_f. More specifically, h_F is the height measured from the elevation of the GaAs membrane **12** to the full level of fuel in the fuel tank, while h_f is the height measured from the elevation of the GaAs membrane **12** to the current level of fuel in the fuel tank **2** The relationships between the respective pressures P_F and P_f (at fill-up and in flight, respectively) exerted on the GaAs membrane, the fuel density D, and the fuel levels h_F and h_f can be described by the following equations:

$$P_F = \frac{F}{A} = \frac{mg}{A} = \frac{DV_F g}{A} = \frac{Dh_F A g}{A} = Dh_F g \qquad (1)$$

$$h_F = \frac{Dg}{P_F} \qquad (2)$$

$$P_f = Dh_f g \qquad (3)$$

$$h_f = \frac{Dg}{P_f} \qquad (4)$$

In Eqs. (1) through (4), m is the mass of fuel, g is gravitational acceleration, A is the GaAs membrane pressure sensing area, and V_F is the volume of fuel overlying the area A upon fill-up. The relationship of the full fuel level height h_F to fuel density D is given in Eq. (2); the relationship of the in-flight fuel level h_f to fuel density D is given in Eq. (4). Since density D can be determined by the computer system **42** based on the measurement data from the temperature probing spectrometer **36**, the fuel levels h_F and h_f can be determined after the respective pressures P_F and P_f have been measured by the pressure sensing spectrometer **40**.

In FIG. **5**, the optical cavity length L formed by the bottom surface of the GaAs membrane **12** and the confronting surface of the distal end of the optical fiber **8a** is given by the following equation:

$$L = \frac{\lambda_i^2}{2n_{eff} \times \Delta\lambda} \qquad (5)$$

where λ_i is the operating wavelength (e.g., 1550 nm), Δλ is the free spectral range of the optical cavity, and n_{eff} is the index of refraction for air.

Using Eq. (5), L can be determined from the measurement of the free spectral range Δλ. FIG. **6** is a graph showing the pressure sensing reflection intensity over a range of wavelengths for light signals reflected from the GaAs photonic membrane **12** to the pressure sensing spectrometer **40**. As seen in FIG. **6**, Δλ can be measured by pumping a 1550-nm broadband spectrum of light into the optical fiber **8a** and then acquiring optical signals reflected from the GaAs membrane **12** back into the optical fiber **8**. The pressure-sensing spectrometer **40** then determines the spacing between the reflected signal peaks of respective wavelengths within the bandwidth of the broadband source. This peak wavelength spacing corresponds to the free spectral range Δλ.

The upper curve in FIG. **6** represents the spectrum of the broadband source centered at 1550 nm with a flat spectral width of about 40 nm. The reflected signal spectrum from the GaAs membrane is shown in the lower part of FIG. **6**. The peaks in this spectrum are the resonant peaks of the Fabry-Pérot resonator cavity (OC in FIG. **6**) formed between the surface of the distal end of the optical fiber **8a** and the confronting bottom surface of the GaAs membrane **12**. The spacing between these periodic resonant peaks is the free spectral range Δλ. As the fuel level change, the free spectral range is instantaneously measured by the pressure sensing spectrometer **40** (see FIG. **1**). This information is output to the computer system **42**, which performs computations to determine the fuel level

After the optical cavity length L has been measured, the current fuel pressure P_f can be derived from L using the following equations, which apply the mechanical theory of membranes:

$$\Delta L = 0.318 l^3 \sqrt[3]{\frac{P_f l}{Eh}} \qquad (6)$$

$$P_f = \frac{Eh(\Delta L)^3}{0.0322 l^4} \qquad (7)$$

where ΔL is change in the optical cavity length due to the displacement or deflection of the GaAs membrane **12**, l is the membrane width, h is the membrane thickness, and E is Young's modulus. As previously noted, $\Delta L = L_0 - L$, where L_0 is the optical cavity length when the fuel compartment **50** is empty, and L is derived from Eq. (5).

The fuel pressure P_f derived from Eq. (7) can be used in Eq. (4) to derive the height h_f from the elevation of the GaAs membrane **12** to the current level of fuel in the fuel tank **2**. The fuel pressure P_F can be derived in a similar manner and used in Eq. (2) to derive the height h_F from the deflection of the GaAs membrane **12** to the full fuel level.

Referring again to FIG. **1**, the computer system **42** is programmed to perform the calculations previously described and is further programmed to control the light sources and the spectrometers. In particular, the computer system **42** is programmed to monitor the operation of the 850-nm laser source **32** and the 1550-nm broadband source **38**; it also controls the test and measurement function of the temperature probing spectrometer **36** and the fuel pressure sensing spectrometer **40**.

The computer system **42** monitors the 850-nm laser source **32** and the laser driver **34** to provide an automatic temperature control loop **44** to drive the 850-nm laser source **32** for constant light output power over the airplane's operating temperature range and other extreme environmental conditions. For example, the computer system **42** can be programmed to increase the power of the 850-nm laser source **32** to melt any ice formed on the exterior surface of the GaAs membrane **12**. This capability can also be used to clean the exterior surface of the GaAs membrane **12** by slightly heating the membrane with higher 850-nm laser power within the allowable heating limit of the fuel tank **2**.

For more advanced fuel quality monitoring, the sensor system depicted in FIG. **1** can be enhanced by adding components which monitor the fuel's chemical composition. This enhancement is shown in FIG. **7**. The system depicted in FIG. **7** differs from that shown in FIG. **1** in that a 1060-nm laser source **46** and a Raman spectrometer **48** for determining fuel chemical composition are added; the 1×4 fiber optic coupler **28** is replaced by a 1×6 fiber optic coupler **30**; and a pair of optical fibers **8g** and **8h** are added to connect the 1×6 fiber optic coupler **30** to the 1060-nm laser source **46** and the Raman spectrometer **48**. These components are used for monitoring the fuel chemical composition in the fuel tank **2** for fuel quality assurance. The optical fiber **8g** is connected with the 1060-nm laser source **46** and the optical fiber **8h** is connected to the Raman spectrometer **48**. The 1060-nm laser source **46** is optically coupled into the optical fiber **8a** inside the fuel tank **2** through the 1×6 fiber optic coupler **30**. The scattering optical signal from the fuel occupying the space above the GaAs membrane **12** passes through the membrane, enters the distal end of the optical fiber **8a**, and is then coupled into the Raman spectrometer **48** through the 1×6 fiber optic coupler **30**.

FIG. **8** is a diagram demonstrating the principle underlying the method of sensing the fuel chemical composition employed by the fiber optic fuel sensor system schematically depicted in FIG. **7**, which method uses a GaAs photonic membrane **12** and the Raman technique. The 1060-nm laser beam that is coupled into the optical fiber **8a** is transparent to the GaAs membrane **12** (as indicated by the dashed arrow pointing upward in FIG. **8**). This is due to the larger band gap of GaAs as compared to the photon energy of the 1060-nm laser beam. Taking advantage of the GaAs transparency to 1060-nm coherent light, the 1060-nm laser beam passes through the GaAs membrane **12** and into the space above the membrane, which is occupied by the fuel. The 1060-nm photons excite the electrons in the fuel molecules to higher vibration states. As these excited electrons relax to their respective ground states, they emit photons which have less energy than the absorbed photon, producing a shift in wavelength from the 1060-nm source wavelength. This energy difference is the well-known Stokes shift of the material being excited. Different molecules have different Stokes shifts, which property can be used to determine the chemical composition of the fuel. The chemical composition at different times can be compared to indicate changes in the fuel's molecular structure. Monitoring the fuel molecular

structure is very important for fuel quality assurance. The Raman scattering signal is coupled through the GaAs membrane **12** back into the optical fiber **8a** inside the fuel tank **2** and then to the Raman spectrometer **48** outside the fuel tank **2**. The Raman spectrometer **48** then analyzes the spectrum of the light returned from the fuel and outputs a Raman "signature" containing information representing the signal intensity as a function of wave number. The Raman spectrometer **48** outputs those signatures to the computer system **42**, which is programmed to compare an incoming Raman signatures to a reference Raman signature, determine the respective shifts in peak wavelengths manifested in the incoming Raman signature, and then identify any changes in fuel chemical composition based on those shifts in peak wavelength.

FIG. **9** is a graph showing shifts in peak signal intensity versus wave number detected by the Raman spectrometer **48**. These shifts in peak signal intensities indicate changes in fuel chemical composition. In the example shown in FIG. **9**, one Raman signature (indicated as the "Reference Signature" in FIG. **9**) represents the Raman spectrum for fuel having an initial chemical composition. The other Raman signature in FIG. **9** represents the Raman spectrum for fuel having a chemical composition which deviates from the initial chemical composition represented by the first Raman signature. Respective shifts in peak wavelengths are indicated by $\Delta\lambda_1$, $\Delta\lambda_2$ and $\Delta\lambda_3$ in FIG. **9**. These shifts indicate that a change in fuel chemical composition has occurred.

The computer system **42** monitors the 1060-nm laser source **46** for constant output power over the airplane's operating temperature, and it also monitors the operation of the Raman spectrometer **48** for calibration, detection and measurement.

The optical coupler **28** and optical fibers **8c** through **8f** depicted in FIG. **1** form an optical network. Similarly, the optical coupler **30** and optical fibers **8c** through **8h** depicted in FIG. **7** form an optical network

The fiber optic sensor disclosed above uses proven and qualified optical fibers, optical components and measurement equipment. No capacitance sensing and measurement are required; the sensor has no active electronic operation inside the fuel tank. No shielding/bonding/grounding of signal wiring is required. There is no possibility of igniting the fuel. The sensor is not afflicted with complications due to stray wiring capacitance/inductance. As a result of using optical fuel sensors to measure fuel levels, the weight and cost of an airplane can be reduced. Also the sensing optical fiber is not exposed or in contact with the fuel.

Each optical fiber is a flexible, optically transparent or translucent fiber made of extruded glass or plastic. It can function as a waveguide or light pipe to transmit light between the two ends of the fiber. Optical fibers typically include a transparent or translucent core having a relatively higher index of refraction surrounded by a transparent or translucent cladding material having a relatively lower index of refraction. Light is kept in the core by total internal reflection. This causes the optical fiber to act as a waveguide.

The computer system **42** may comprise one or more dedicated microprocessors or one or more general-purpose computers, and may calculate the measured level (i.e., height) of the fuel by using a look-up table, a calibration curve, or by solving equations, as appropriate. A fuel gauge (not shown in the drawings) displayed in the cockpit may be controlled to indicate the amount of fuel present within the fuel tank based on the spectrometry data received by the computer system **42**.

The computer system **42** may be a computer or part of a flight control system located on an aircraft. In identifying the amount of fuel present in an irregular-shaped fuel tank, the computer system **42** may execute various routines to calculate the amount of fuel present based on data received from multiple GaAs membranes appropriately placed in various compartments of the fuel tank. The fuel information processing software may include routines that take into account the shape of the fuel tank to determine the amount of fuel remaining in the fuel tank. The fuel information processing software may further include routines for calibrating processes to form a baseline before a first use or to maintain accuracy of fuel readings. The readings provided by the computer system **42** to the fuel gauge may be integrated or averaged before presentation and may be provided at different time intervals.

In the example shown in FIGS. **1** and **7**, optical fibers are used to measure the level of fuel in a fuel tank. In other embodiments, the same apparatus may be used to detect other liquids. For example, the system described above may be used to detect the presence of water in a container or hydraulic fluids in a reservoir for a hydraulic system. The illustration of detecting fuel in a fuel tank is presented for purposes of illustration and not meant to limit the manner in which the systems shown in FIGS. **1** and **7** may be used.

A wing fuel tank system that uses electrical sensors can be retrofitted by substituting the optical sensors disclosed herein. Double shielded electrical wiring for the electrical sensors can be replaced with light and flexible plastic optical fiber, eliminating weight from the wiring and supporting brackets, and eliminating electromagnetic effects from lightning, shorting, fraying of electrical wiring.

While optical fuel sensors having membranes made of direct band gap semiconductor material have been described with reference to various embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the teachings herein. In addition, many modifications may be made to adapt the concepts and reductions to practice disclosed herein to a particular situation. Accordingly, it is intended that the subject matter covered by the claims not be limited to the disclosed embodiments.

As used in the claims, the term "computer system" should be construed broadly to encompass a system having at least one computer or processor, and which may have multiple computers or processors that communicate through a network or bus. As used in the preceding sentence, the terms "computer" and "processor" both refer to devices having a processing unit (e.g., a central processing unit) and some form of memory (i.e., computer-readable medium) for storing a program which is readable by the processing unit.

In addition, the method claims set forth hereinafter should not be construed to require that the steps recited therein be performed in alphabetical order (any alphabetical ordering in the claims is used solely for the purpose of referencing previously recited steps) or in the order in which they are recited. Nor should they be construed to exclude any portions of two or more steps being performed concurrently or alternatingly.

The invention claimed is:

1. A system for storing a liquid, comprising:
a reservoir comprising an enclosure;
a chamber-defining structure disposed inside said enclosure that divides an internal volume of said enclosure into a storage compartment and a chamber which are hermetically sealed from each other, said chamber-

defining structure comprising a membrane having a top surface that partly defines said storage compartment and a bottom surface that partly defines said chamber, and a housing that supports said membrane and partly defines said chamber, wherein said membrane is made of a semiconductor material that has a direct band gap;
an optical fiber having a length disposed inside said chamber, said length of optical fiber having a distal end with a surface that confronts said bottom surface of said membrane with a gap therebetween,
a broadband light source for outputting broadband light;
a first spectrometer for converting received broadband light into an electrical signal representing a characteristic of the received broadband light;
a coherent light source for outputting coherent light;
a second spectrometer converting received coherent light into an electrical signal representing a characteristic of the received coherent light;
an optical coupler which optically couples said broadband light source, said coherent light source, and said first and second spectrometers to said optical fiber; and
a computer system programmed to compute a value of a pressure of the liquid contained in the reservoir based on electrical signals received from said first spectrometer following the output of broadband light by said broadband light that impinges on and is reflected from said membrane and compute a value of a temperature of the liquid contained in the reservoir based on electrical signals received from said second spectrometer following the output of coherent light by said coherent light source that impinges on and is reflected from said membrane.

2. The system as recited in claim **1**, wherein said membrane is sufficiently thin that said membrane is capable of flexing upward or downward when a magnitude of a pressure being exerted on its top surface changes.

3. The system as recited in claim **2**, wherein said membrane has a thickness in a range of 0.01 to 0.5 mm.

4. The system as recited in claim **1**, wherein said semiconductor material is gallium arsenide or indium phosphide.

5. The system as recited in claim **1**, wherein said optical fiber is a single-mode or multi-mode optical fiber.

6. The system as recited in claim **1**, further comprising:
a filter support wall that surrounds a space inside said storage compartment that overlies said membrane; and
a filter supported by said filter support wall, said filter being configured to admit liquid into said space while excluding particulate matter from outside said space.

7. The system as recited in claim **1**, wherein said gap has a dimension such that said bottom surface of said membrane and a confronting surface of said distal end of said optical fiber form a Fabry-Pérot resonator cavity.

8. The system as recited in claim **1**, further comprising a fiber optic connector seated in and hermetically sealed to an opening in said enclosure and to an opening in said housing, wherein another end of said length of said optical fiber is coupled to said fiber optic connector.

9. The system as recited in claim **1**, wherein said reservoir is incorporated in a wing of an aircraft.

10. A system for storing a liquid, comprising:
a storage tank;
a hermetically sealed package disposed inside said storage tank; said hermetically sealed package comprising a membrane and a length of optical fiber, wherein said membrane has a top surface that is part of an exterior surface of said hermetically sealed package and a bottom surface that is part of an interior surface of said

hermetically sealed package, wherein said membrane is made of a semiconductor material that has a direct band gap, and said length of optical fiber has a distal end with a surface that confronts said bottom surface of said membrane with a gap therebetween;

a laser source for outputting coherent light;

a temperature probing spectrometer for converting received coherent light into an electrical signal representing a characteristic of the received coherent light;

an optical fiber network which optically couples said laser source and said temperature probing spectrometer to said length of optical fiber; and

a computer system programmed to determine a temperature of liquid contained in said storage tank based on electrical signals received from said temperature probing spectrometer following output of coherent light from said laser source that impinges on and is reflected from said membrane.

11. The system as recited in claim 10, wherein said semiconductor material is gallium arsenide or indium phosphide.

12. A system for storing a liquid, comprising:

a storage tank;

a hermetically sealed package disposed inside said storage tank; said hermetically sealed package comprising a membrane and a length of optical fiber, wherein said membrane has a top surface that is part of an exterior surface of said hermetically sealed package and a bottom surface that is part of an interior surface of said hermetically sealed package, wherein said membrane is made of a semiconductor material that has a direct band gap, and said length of optical fiber has a distal end with a surface that confronts said bottom surface of said membrane with a gap therebetween;

a first optical source for outputting light;

a first spectrometer for converting received light into an electrical signal representing a characteristic of the received light; and

an optical fiber network which optically couples said first optical source and said first spectrometer to said length of optical fiber, said optical fiber network comprising an optical coupler,

wherein said first optical source is a laser source that produces coherent light having a wavelength, said membrane is transparent to coherent light of said wavelength, and said first spectrometer is a Raman spectrometer which receives light scattered back though said membrane by liquid contained in said storage tank, further comprising a computer system programmed to determine a chemical composition of liquid contained in said storage tank based on electrical signals received from said Raman spectrometer following output of said coherent light from said laser source.

13. The system as recited in claim 12, further comprising:

a second optical source for outputting light; and

a second spectrometer for converting received light into an electrical signal representing a characteristic of the received light,

wherein the optical fiber network optically couples said second optical source and said second spectrometer to said length of optical fiber.

14. The system as recited in claim 13, wherein said second optical source is a laser source, said second spectrometer is a temperature probing spectrometer, and said computer system is further programmed to determine a temperature of liquid contained in said storage tank based on electrical

signals received from said temperature probing spectrometer following output of light from said second optical source.

15. The system as recited in claim 13, wherein said second optical source is a broadband light source, said second spectrometer is a pressure sensing spectrometer, and said computer system is further programmed to determine a pressure of liquid contained in said storage tank based on electrical signals received from said pressure sensing spectrometer following output of light from said second optical source.

16. The system as recited in claim 12, wherein said semiconductor material is gallium arsenide or indium phosphide.

17. A method for determining a temperature of liquid stored in a storage tank, comprising:

placing a hermetically sealed package inside the storage tank, the hermetically sealed package comprising a membrane and a length of optical fiber, wherein the membrane has a top surface that is part of an exterior surface of the hermetically sealed package and a bottom surface that is part of an interior surface of the hermetically sealed package, wherein the membrane is made of a semiconductor material that has a direct band gap, and the length of optical fiber has a distal end with a surface that confronts the bottom surface of the membrane with a gap therebetween;

emitting coherent light from a laser source that enters a proximal end of the optical fiber, exits the distal end of the optical fiber, and impinges on the bottom surface of the membrane;

guiding coherent light from the membrane that enters the distal end of the optical fiber toward a proximal end of the optical fiber after the coherent light has been emitted by the first optical source;

measuring a first property of the coherent light that exited the proximal end of the optical fiber using a temperature probing spectrometer after the coherent light has been emitted by the laser source; and

processing electronic data output by the temperature probing spectrometer to determine a temperature of liquid disposed inside the storage tank and on top of the membrane.

18. The method as recited in claim 17, further comprising:

emitting broadband light from a broadband light source that enters a proximal end of the optical fiber, exits the distal end of the optical fiber, and impinges on the bottom surface of the membrane;

guiding broadband light from the membrane that enters the distal end of the optical fiber toward a proximal end of the optical fiber after the broadband light has been emitted by the second optical source;

measuring a second property of the broadband light that exited the proximal end of the optical fiber using a pressure spectrometer after the broadband light has been emitted by the broadband light source; and

processing electronic data output by the pressure spectrometer to determine a pressure of liquid disposed inside the storage tank and on top of the membrane.

19. The method as recited in claim 18, further comprising:

calculating a density of the liquid contained in the storage tank based on the determined temperature; and

calculating a level of the liquid contained in the storage tank based on the calculated density and the determined pressure.

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