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# Thermal sensor, thermal sensor array, electronic apparatus including the thermal sensor, and operating method of the thermal sensor


## Abstract

A thermal sensor, a thermal sensor array, an electronic apparatus including the thermal sensor, and an operating method of the thermal sensor are provided. The thermal sensor includes a first region onto which first infrared light is incident, a visible light radiation region configured to radiate visible light generated by incidence of the first infrared light on the first region, a second region onto which second infrared light is incident, and an image sensor configured to receive the visible light radiated from the visible light radiation region. The first region, the second region, and the visible light radiation region each include a nonlinear optical material.



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## Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS
(1) This application claims the benefit of Russian Patent Application No. 2022124059, filed on Sep. 12, 2022, in the Russian Patent Office and Korean Patent Application No. 10-2023-0092468, filed on Jul. 17, 2023, in the Korean Intellectual Property Office, the disclosures of which are incorporated herein by reference in their entireties.
BACKGROUND
1. Field
(2) The disclosure relates to an infrared sensor, and more particularly, to a thermal sensor, a thermal sensor array, an electronic apparatus including the thermal sensor, and an operating method of the thermal sensor.
2. Description of the Related Art
(3) Infrared (IR) image sensors (e.g., thermal sensors) use electronic signal readout for sensing. That is, data is obtained by measuring a current or a voltage.
(4) These IR image sensors may require high sensitivity, small size, and compatibility with complementary metal-oxide-semiconductor (CMOS) technology.
(5) IR image sensors may be classified into sensors compatible with the CMOS technology and sensors incompatible with the CMOS technology. The IR image sensors compatible with the CMOS technology and the IR image sensors incompatible with the CMOS technology may be different from each other in terms of sensitivity and design.
SUMMARY
(6) One or more example embodiments provide a low-cost thermal sensor, a method of operating the thermal sensor, and an electronic apparatus including the thermal sensor.

(7) Further, one or more example embodiments provide a thermal sensor compatible with a CMOS image sensor (compatible with CMOS technology).
(8) Still further, one or more example embodiments provide a compact thermal sensor with increased degree of integration.
(9) Still further, one or more example embodiments provide a thermal sensor array including the thermal sensor, and an electronic apparatus including the thermal sensor array.
(10) Additional aspects will be set forth in part in the description which follows and, in part, will be apparent from the description, or may be learned by practice of the presented embodiments.
(11) According to an aspect of the disclosure, a thermal sensor may include a first region onto which first infrared light is incident; a visible light radiation region configured to emit visible light that is generated in response to the first infrared light being incident on the first region; a second region onto which second infrared light is incident; and an image sensor configured to receive the visible light emitted from the visible light radiation region, wherein each of the first region, the second region, and the visible light radiation region may include a nonlinear optical material.
(12) In an example, the first region, the second region, and the visible light radiation region may be connected to one another. The visible light radiation region may be in the second region. In an example, the visible light radiation region may be located between an edge of the second region and a center of the second region, and surround the center.
(13) In an example, the visible light radiation region may be in an outer boundary of the second region.
(14) The visible light may include harmonics generated by incidence of the first infrared light on the first region.
(15) In an example, the visible light radiation region may include a decoupler arranged at a harmonic resonance distance where the harmonics are reached. The decoupler may include a diffraction grating.
(16) In an example, the thermal sensor may include a resonator optically coupled to the image sensor, a waveguide configured to form optical coupling between a part of the waveguide and the resonator; a light source provided to emit the first infrared light into the waveguide; and a controller configured to change a wavelength of light emitted from the light source to correspond to a change of a resonant wavelength of the resonator, wherein the resonator may include a top surface and a side surface, and a region of the side surface of the resonator, which forms the optical coupling with the waveguide, may correspond to the first region, the top surface of the resonator corresponds to the second region, and the visible light radiation region may be a partial region of the top surface.
(17) In an example, a portion of the waveguide, optically coupled to the resonator, may be linear or curved. The waveguide may include a non-linear optical material.
(18) In an example, the thermal sensor may further include a transparent substrate including a through-hole and a thermally insulating bridge provided to connect the transparent substrate to the resonator and support the resonator, in which the resonator is located inside the through-hole and does not directly contact the substrate, and a part of the through-hole except for the resonator and the thermally insulating bridge is filled with a thermally insulating layer.
(19) In an example, the image sensor may include a complementary metal oxide semiconductor (CMOS) image sensor.
(20) In an example, the nonlinear optical material may include a silicon nitride.
(21) In an example, a plurality of through-holes may be provided to be separated from each other in the transparent substrate, the resonator, the thermally insulating bridge, and the thermally insulating layer may be provided in each of the plurality of through-holes, and the waveguide may be shared by the resonators provided in the plurality of through-holes.
(22) In an example, the plurality of through-holes may be arranged to form a matrix, an optical splitter may be further provided between the light source and the plurality of through-holes, the

waveguide may include a plurality of waveguides, and one of the plurality of waveguides may be provided between the light source and the optical splitter, and the others of the plurality of waveguides may be arranged in a one-to-one correspondence with rows or columns of the plurality of through-holes.
(23) According to another aspect of the disclosure, a first electronic apparatus (thermal imaging camera) includes an infrared optical system configured to form a thermal image of an object and a thermal sensor arranged at a focal distance of the infrared optical system on which the thermal image is imaged. The thermal sensor may include a first region onto which first infrared light is incident, a visible light radiation region configured to radiate visible light generated by incidence of the first infrared light on the first region, a second region onto which the thermal image is incident, and an image sensor provided at a position to receive the visible light radiated from the visible light radiation region, and the first region, the second region, and the visible light radiation region each may include a nonlinear optical material.
(24) In an example, the first electronic apparatus may further include a resonator optically coupled to the image sensor and including the nonlinear optical material, a waveguide close to the resonator to form optical coupling between a part thereof and the resonator, a light source provided to irradiate the first infrared light into the waveguide, and a controller provided to change a wavelength of light radiated from the light source to correspond to a change of a resonant wavelength of the resonator and connected to the image sensor. The resonator may include a top surface and a side surface, and a region of the side surface of the resonator, which forms optical coupling with the waveguide, may correspond to the first region, the top surface of the resonator may correspond to the second region, and the visible light radiation region may be a partial region of the top surface.
(25) According to another aspect of the disclosure, a second electronic apparatus may include the thermal sensor or the first electronic apparatus according to an embodiment described above.
(26) According to another aspect of the disclosure, an operating method of a thermal sensor includes receiving visible light radiated from a resonator of the thermal sensor before shifting of a resonant wavelength of the resonator to obtain first data about a first visible image of the resonator, receiving visible light radiated from the resonator after shifting of the resonant wavelength of the resonator due to incidence of external infrared light onto the resonator to obtain second data about a second visible image of the resonator, obtaining, based on the first data and the second data, third data about shifting of the resonant wavelength of the resonator due to the incidence of the external infrared light, and calculating, based on the third data, a temperature of the resonator and an intensity of the external infrared light on the resonator due to the incidence of the external infrared light.
(27) In an example, the visible light may be generated from infrared light introduced into the resonator from inside of the thermal sensor to correspond to the resonant wavelength of the resonator, and the resonator may include a decoupler configured to radiate the visible light.
(28) In an example, the third data may be transmitted to a display device.

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## Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) The above and other aspects, features, and advantages of certain embodiments will be more apparent from the following description taken in conjunction with the accompanying drawings, in which:
(2) FIG. **1** is a plane view of a first thermal sensor according to an embodiment;
(3) FIG. **2** is a cross-sectional view of the first thermal sensor of FIG. **1** cut in a direction **2-2′**;
(4) FIG. **3** is a cross-sectional view of the first thermal sensor when a thermally insulating layer of

FIG. **2** is filled with a thermally insulating material layer;
(5) FIG. **4** is a cross-sectional view of the first thermal sensor of FIG. **1** cut in a direction **4-4′**;
(6) FIG. **5** is a cross-sectional view of a case where a thermally insulating bridge of FIG. **4** is divided into two separated parts;
(7) FIG. **6** is a cross-sectional view of a case where a thermally insulating layer of FIG. **5** is filled with a thermally insulating material layer;
(8) FIG. **7** is a cross-sectional view of a case where a thermally insulating bridge of FIG. **5** is separated from an image sensor;
(9) FIG. **8** is a cross-sectional view of a case where a thermally insulating layer of FIG. **7** is filled with a thermally insulating material layer;
(10) FIG. **9** is a plane view of a case where, in an optical coupling region where a waveguide of a thermal sensor according to an embodiment and a microresonator are located close to each other, light leaking from the waveguide enters the microresonator and circulated light is generated in the microresonator as the light enters the microresonator;
(11) FIG. **10** is a cross-sectional view of a case where visible light is radiated from a decoupler of the microresonator of FIG. **9** and is incident onto an image sensor under the microresonator;
(12) FIGS. **11** and **12** are plane views of another example of a decoupler of a microresonator of a thermal sensor according to an embodiment;
(13) FIG. **13** is a plane view of a case where a waveguide of an optical coupling region is curved in the first thermal sensor of FIG. **1**;
(14) FIG. **14** is a graph of harmonic generation efficiency of a thermal sensor according to an embodiment;
(15) FIG. **15** is a plane view of a first thermal sensor according to an embodiment;
(16) FIG. **16** is a plane view of a second thermal sensor according to an embodiment;
(17) FIG. **17** is a perspective view of two rows and two columns selected from a thermal sensor array of FIG. **15** or **16**;
(18) FIG. **18** is a block diagram of a thermal imaging camera as an example of a first electronic apparatus according to an embodiment; and
(19) FIG. **19** is a block diagram of schematic configuration of a second electronic apparatus according to an embodiment.

## DETAILED DESCRIPTION

(20) Reference will now be made in detail to embodiments, examples of which are illustrated in the accompanying drawings, wherein like reference numerals refer to like components throughout. In this regard, the present embodiments may have different forms and should not be construed as being limited to the descriptions set forth herein. Accordingly, the embodiments are merely described below, by referring to the figures, to explain aspects. Expressions such as “at least one of,” when preceding a list of components, modify the entire list of components and do not modify the individual components of the list. Expressions such as “at least one of,” when preceding a list of components, modify the entire list of components and do not modify the individual components of the list.
(21) Hereinbelow, a thermal sensor, a thermal sensor array, an electronic apparatus including the thermal sensor, and an operating method of the thermal sensor according to an embodiment will be described in detail with reference to the accompanying drawings. In this process, a thickness of a layer or region shown in the drawings may be shown as being slightly exaggerated for clarity of a specification.
(22) Embodiments to be described are merely examples, and various modifications may be made from such embodiments. In a layer structure described below, an expression “above” or “on” may include not only an expression “directly on in contact” but also an expression “on contactlessly”. In the following description, the same reference numeral in each drawing may refer to the same member.

(23) Singular forms include plural forms unless apparently indicated otherwise contextually. When a portion is referred to as "comprises" a component, the portion may not exclude another component but may further include another component unless stated otherwise.
(24) The use of the terms of "the above-described" and similar indicative terms may correspond to both the singular forms and the plural forms. When there is no apparent description of the order of operations constituting a method or a contrary description thereof, the operations may be performed in an appropriate order. The disclosure is not necessarily limited according to the describing order of the operations.
(25) The term used herein such as "unit" or "module" indicates a unit for processing at least one function or operation, and may be implemented in hardware, software, or in a combination of hardware and software.
(26) Connections of lines or connection members between components shown in the drawings are illustrative of functional connections and/or physical or circuit connections, and in practice, may be represented as alternative or additional various functional connections, physical connections, or circuit connections.
(27) The use of all examples or exemplary terms is only to describe technical spirit in detail, and the scope is not limited by these examples or terms unless limited by the claims.
(28) FIG. **1** shows a first thermal sensor **100** according to an embodiment.
(29) Referring to FIG. **1**, the first thermal sensor **100** may include a substrate **30**, a microresonator **40**, a waveguide **70** positioned in proximity to the microresonator **40**, and a light source **80** configured to inject light into the waveguide **70**. In an example, the substrate **30** may have transparency to incident light, including visible light. In an example, the substrate **30** may be thermally stabilized not to affect an operation of the resonator **40**, and a temperature throughout the substrate **30** may be constant or substantially constant. In an example, the substrate **30** may include a silicon oxide substrate or a silicon oxide. A through-hole **30***h* may be formed in the substrate **30**. The through-hole **30***h* may have a circular planar shape, but may also have a non-circular shape (e.g., a square shape). In an example, the through-hole **30***h* may be provided in a ring shape. The resonator **40** may be provided in the through-hole **30***h*. The planar shape of the resonator **40** may be or may not be the same as the planar shape of the through hole **30***h*. In an example, the planar shape of the through-hole **30***h* may be rectangular, and the planar shape of the resonator **40** may be circular. An edge of the resonator **40** may be separated from a boundary of the through-hole **30***h*. A distance between the resonator **40** and the boundary of the through-hole **30***h* may be constant or substantially constant from a circumference of the resonator **40**, without being limited thereto. A material layer substantially thermally insulated, i.e., a thermally insulating layer **60** may be positioned between the resonator **40** and the substrate **30**. The thermally insulating layer **60** may be a gas layer (e.g., an air layer) or a material layer (e.g., a solid layer) that is not gaseous. In an example, the thermally insulating layer **60** may be a gas layer at a substantially lower pressure compared to atmospheric pressure, and that is, the thermally insulating layer **60** may be substantially vacuum (layer).
(30) Light may be incident onto the resonator **40** from outside of the thermal sensor **100**. The resonator **40** may include a nonlinear optical material (substance) that absorbs the light (hereinafter, "outside light") incident from outside of the thermal sensor **100** or may be formed of the substance. In an example, the outside light may be or include light of an infrared region. In an example, the outside light may include at least one of short wavelength infrared (SWIR), middle wavelength infrared (MWIR) light, or long wavelength infrared (LWIR). The resonator **40** may completely or partially absorb the outside light. In an example, the resonator **40** may include or be formed of a first material that is a nonlinear optical material capable of absorbing 40% or more, 50% or more, 60% or more, 70% or more, 80% or more, 90% or more, or 95% or more of the outside light incident through a region to which the outside light is incident. In an example, the first material may include, but is not limited to, a silicon nitride. When the resonator **40** absorbs the outside light,

the resonator **40** may be heated as a result of absorbing the outside light, and a temperature of the resonator **40** may be greater than before the outside light is absorbed. A temperature change of the resonator **40** due to a thermo-optic effect may cause a refractive index change of the resonator **40**, such that a resonance wavelength (or resonant wavelength) of the resonator **40** before absorption of the outside light may change after absorption of the outside light. A degree of change of the resonant wavelength, i.e., a shift of the resonant wavelength, of the resonator **40** may be proportional to an intensity of the outside light.

(31) The resonator **40** may include a first decoupler **42** in a region to which the outside light is incident. As the first decoupler **42** is included, visible light generated in the resonator **40** may be emitted outward from the resonator **40**. This will be described in detail later. In light of these functions of the first decoupler **42**, the first decoupler **42** may be described as a light splitter, a light separating element, a light separating member, and a light separating structure, and a region including the first decoupler **42** may be expressed as a visible light radiation region. As the resonator **40** includes a nonlinear optical material, when the wavelength of light (e.g., infrared light) introduced into the resonator **40** from the waveguide **70** corresponds to the resonant wavelength of the resonator **40**, second harmonics that are visible light may be generated inside the resonator **40**. The second harmonics may be emitted outward from the resonator **40** by the first decoupler **42**. As a result, the visible light emitted outward from the resonator **40** by the first decoupler **42** may have the second harmonics. The first decoupler **42** may be positioned within a harmonic resonance distance whether the second harmonics are reached.

(32) While the entre waveguide **70** may be provided in a straight line, it is not limited to such an arrangement. For example, as shown in FIG. **13**, some section of the waveguide **70** may have a curved form. The waveguide **70** may function as a conduit conveying a part of first light emitted from the light source **80** to the thermal sensor **100**. For example, the waveguide **70** may be arranged such that a part of the waveguide **70** passes between the resonator **40** and the boundary of the through-hole **30***h*. The part of the waveguide **70** may be close to the resonator **40**. In an example, the waveguide **70** may be disposed in proximity to the resonator **40** such that optical coupling may occur between the waveguide **70** and the resonator **40**. Thus, light leaking from the waveguide **70** may enter the resonator **40**. The light leaking from the waveguide **70** may be evanescent light having an intensity decreasing exponentially. Reference numeral **90** may indicate a region where optical coupling occurs between the waveguide **70** and the resonator **40** due to the evanescent light. In a region **90** where optical coupling occurs, a gap or a separation distance between the waveguide **70** and the resonator **40** may be less than a distance between the boundary of the through-hole **30***h* and the resonator **40**.

(33) In an example, a material (substance) of the waveguide **70** may be or include a nonlinear optical material (substance). In an example, the material of the waveguide **70** may be different from or the same as the material of the resonator **40**. The waveguide **70** may be thermally stabilized. That is, the total temperature of the waveguide **70** may be substantially constant. Thus, the waveguide **70** may not affect an operation of the resonator **40**. In an example, the nonlinear optical material of the waveguide **70** may include a silicon nitride but be not limited to there.

(34) The light source **80** may be arranged at an end of the waveguide **70**. The light source **80** may be directly or optically connected to an end of the waveguide **70**. The light source **80** may be provided in the waveguide **70** to supply first light L**1**. In an example, the first light L**1** may include light in an infrared band. In an example, the light source **80** may include a structure for radiating near-infrared light into the waveguide **70**. In an example, the light source **80** may include a laser for radiating near-infrared light as the first light L**1**. In an example, an operation of the light source **80** may be controlled in real time by a controller. In an example, a wavelength of the first light L**1** radiated from the light source **80** may be tuned in real time according to an operation of the resonator **40**. That is, the wavelength of the first light L**1** radiated from the light source **80** may be variable in real time. In an example, a variable range of the wavelength of the first light L**1** may

include a variable range of a resonant wavelength of the resonator **40**. For example, when the resonant wavelength of the resonator **40** is changed as the outside light is incident onto the resonator **40**, the wavelength of the first light L**1** radiated from the light source **80** may be adjusted to correspond to the changed resonant wavelength of the resonator **40**. Such adjustment may be possible by sweeping the light source **80** to the possible resonant wavelength range of the resonator **40**.

(35) A plurality of thermally insulating bridges **50** are provided between the boundary of the through-hole **30***h* and the resonator **40**. The thermally insulating bridges **50** may be arranged separated from each other in a rotation direction. In an example, the thermally insulating bridges **50** may be provided perpendicularly to each other, but arrangement thereof is not limited thereto. In an example, the thermally insulating bridges **50** may be provided such that two adjacent bridges form an acute angle. The thermally insulating bridges **50** may be provided to connect the resonator **40** to the substrate **30**. In an example, the thermally insulating bridges **50** may have such low thermal conductivity as to minimize a loss of heat generated in the resonator **40** as the outside light is incident onto the resonator **40**. Thus, as the outside light is incident onto the resonator **40**, heat generated in the resonator **40** may be accumulated in the resonator **40** without leaking, such that a temperature change in the resonator **40** may be greater than a case with leakage of heat. This may directly lead to improved sensitivity of the thermal sensor **100**. The thermally insulating bridges **50** may have low thermal conductivity, but excessively low thermal conductivity may be avoided. That is, heat accumulated in the resonator **40** may be transmitted to the substrate **30** after a certain time to prevent the heat accumulated in the resonator **40** from staying in the resonator **40** too long. A material of the thermally insulating bridges **50** may be selected considering these points. In an example, the material of the thermally insulating bridges **50** may be the same as the material of the substrate **30**, without being limited thereto. In an example, the thermally insulating bridges **50** may include, but not limited to, a silicon oxide. The thermally insulating bridges **50** may be a member (support) supporting the resonator **40**.

(36) FIG. **2** is a cross-sectional view of the first thermal sensor of FIG. **1** cut in a direction **2-2**′.

(37) Referring to FIG. **2**, the first thermal sensor **100** may further include an image sensor **20** and a resonator layer RL**1** that are sequentially stacked. The image sensor **20** may be or include a complementary metal-oxide semiconductor (CMOS) image sensor. In an example, the image sensor **20** may be a black/white image sensor or a color image sensor. The image sensor **20** may include a substrate **20***a* including a readout integration circuit (ROIC) and a plurality of pixels **20***b* provided thereon. In an example, each pixel **20***b* may or may not include a color filter. In an example, each pixel **20***b* may include a meta structure layer that performs color separation and light collecting (focusing) in place of a color filter. In an example, the meta structure layer may also perform a role of a micro-lens. Accordingly, when each pixel **20***b* includes the meta structure layer, each pixel **20***b* may not include both a micro-lens and a color filter.

(38) The resonator layer RL**1** may be expressed as a bolometer resonator layer in that the thermal sensor **100** senses or detects infrared light like a bolometer. The resonator layer RL**1** may include the substrate **30** and the resonator **40** described with reference to FIG. **1**. In an example, the resonator light RL**1** may include the light source **80** and the waveguide **70**.

(39) The resonator **40** provided between the substrates **30** may be separated from the image sensor **20**. The resonator **40** may be separated from the substrate **30** horizontally. The resonator **40** may have a first thickness t**1** and a first diameter D**1**. The first thickness t**1** and a radius D½ of the resonator **40** may be related to radiation of the second harmonics, which are the visible light generated in the resonator **40**, to the outside of the resonator **40** through the first decoupler **42**. Thus, during a manufacturing process of the thermal sensor **100**, the first thickness t**1** and the first diameter D**1** of the resonator **40** may be set based on generation of the second harmonics in the resonator **40**.

(40) The first decoupler **42** of the resonator **40** may be, but not limited to, a concave pattern (an

engraved pattern) formed in a top surface of the resonator **40**. The first decoupler **42** may be a diffraction grating. Thus, light incident onto the first decoupler **42** may be diffracted and radiated to the outside of the resonator **40**. Second light **2**L**1** incident onto the first thermal sensor **100** from outside of the first thermal sensor **100** may be the outside light as described above. The second light **2**L**1** may be incident onto the entire top surface on which the first decoupler **42** is formed. Thus, the entire top surface of the resonator **40** may be expressed as a region to which the second light **2**L**1** is incident. The second light **2**L**1** may belong to the infrared region mentioned in the description of FIG. **1**.

(41) In FIG. **2**, the thermally insulating layer **60** between the substrates **30** and under the resonator **40** may be vacuum (layer) or an air layer, but as shown in FIG. **3**, the thermally insulating layer **60** may be filled with a thermally insulating material layer **60′** that is not gaseous. In this case, the resonator **40** may be provided on the thermally insulating material layer **60′**. In an example, a material and thermal conductivity of the thermally insulating material layer **60′** may correspond to those of the thermally insulating bridges **50** described with reference to FIG. **1**.

(42) FIG. **4** shows an example of a cross-section of the first thermal sensor of FIG. **1** cut in a direction **4-4′**. A part different from FIG. **2** will be described.

(43) Referring to FIG. **4**, in the resonator layer RL**1**, the thermally insulating bridge **50** may be provided between the substrates **30** and under the resonator **40**. The thermally insulating bridge **50** may be directly connected to the substrate **30**. The thermally insulating bridge **50** may directly contact a bottom surface of the resonator **40**. The resonator **40** may be supported by the thermally insulating bridge **50**. The thermally insulating bridge **50** may be provided to continuously cross the bottom surface of the resonator **40** from one side to the other. The thermally insulating bridge **50** may contact the bottom surface of the resonator **40** thereon and contact the image sensor **20** thereunder. A thickness t**2** of the thermally insulating bridge **50** may be the same as a thickness of the substrate **30**. A height of the thermally insulating bridge **50** may be the same as a height of the substrate **30**.

(44) Referring to FIGS. **1** and **4** together, the thermally insulating bridge **50** may be regarded as a result (a structure) of a part of the substrate **30** extending into the through-hole **30***h*.

(45) In an example, the thermally insulating bridge **50** may have a structure not crossing the entire bottom surface of the resonator **40** as shown in FIG. **5**.

(46) Referring to FIG. **5**, the thermally insulating bridge **50** may be divided into a first part **50***a* and a second part **50***b* that are separated from each other. The first part **50***a* may contact a part of the bottom surface of the resonator **40**, and the second part **50***b* may contact another part of the bottom surface of the resonator **40**. The first part **50***a* and the second part **50***b* under the resonator **40** may be separated from each other. Under the resonator **40**, the thermally insulating layer **60** between the first part **50***a* and the second part **50***b* of the thermally insulating bridge **50** may be a gas layer or vacuum (layer), but the thermally insulating layer **60** may be filled with a solid thermally insulating material layer **60′** as shown in FIG. **6**.

(47) In an example, the first part **50***a* and the second part **50***b* of the thermally insulating bridge **50** of the first thermal sensor **100** shown in FIG. **5** may be provided separated from the image sensor **20** as shown in FIG. **7**.

(48) Referring to FIG. **7**, the first part **50***a* and the second part **50***b* may be separated from the image sensor **20** while maintaining the contact with the bottom surface of the resonator **40**. As a result, a thickness of the first part **50***a* and the second part **50***b* of the thermally insulating bridge **50** may be less than the thickness of the substrate **30**.

(49) In FIG. **7**, the thermally insulating layer **60** may be a gas layer or vacuum (layer), but the thermally insulating layer **60** may be filled with the thermally insulating material layer **60** that is solid as shown in FIG. **8**.

(50) FIG. **9** is a plane view showing a case where light L**1′** enters the resonator **40** from the waveguide **70** in an optical coupling region **90**. The light L**1′** may leak from the waveguide **70** and

enter the resonator **40** in a region where the waveguide **70** and the resonator **40** are close to each other, and may be, for example, evanescent light having an intensity exponentially decreasing from the waveguide **70** toward the resonator **40**. As a result, in the optical coupling region **90**, the waveguide **70** and the resonator **40** may be optically coupled through the evanescent light. The optical coupling between the waveguide **70** and the resonator **40** through the light L**1**′ may occur when a gap G**1** of the region where the waveguide **70** and the resonator **40** are close to each other falls within a given range. In an example, the gap G**1** may be, but not limited to, about 500 nm.
(51) In an example, the light L**1**′ may be light of an infrared region, e.g., near-infrared light. A wavelength of the light L**1**′ may be variable and correspond to the resonance wavelength of the resonator **40**. That is, when the temperature of the resonator **40** changes due to a thermo-optic effect, the resonant wavelength of the resonator **40** may also be changed. In an example, when the second light **2**L**1** of the infrared region is incident onto the resonator **40**, the temperature of the resonator **40** may increase, and thus the resonant wavelength of the resonator **40** may increase when compared to a resonant wavelength thereof before incidence of the second light **2**L**1**. That is, the resonant wavelength may be shifted. Through such a shift of the resonant wavelength, the wavelength of the first light L**1** radiated into the waveguide **70** from the light source **80** may also be adjusted properly for the resonant wavelength. As a result, when the resonant wavelength of the resonator **40** is shifted, the wavelength of the light L**1**′ entering the resonator **40** from the waveguide **70** in the optical coupling region **90** may also be adjusted appropriately for the shifted resonant wavelength of the resonator **40**.
(52) When the wavelength of the light L**1**′ entering the resonator **40** from the waveguide **70** corresponds to (coincides with or matches) the resonant wavelength of the resonator **40** in the optical coupling region **90**, the light L**1**′ may enter the resonator **40** and propagate while circulating in any one direction (e.g., a counterclockwise direction) through internal total reflection along an edge region (a border region) of the resonator **40**. In this case, the light L**1**′ may propagate in a first whispering gallery mode inside the resonator **40**. Reference numeral WL**1** may indicate first circulated light circulated in the edge region of the resonator **40** in the first whispering gallery mode. The first circulated light WL**1** may have a fundamental mode of the first light L**1** radiated from the light source **80**, and may have the same wavelength as that of the first light L**1**. As the light L**1**′ corresponding to the resonant wavelength of the resonator **40** enters the resonator **40** in the optical coupling region **90**, second circulated light WL**2** may be generated together with the first circulated light WL**1**. The second circulated light WL**2** may correspond to a second harmonic component of the light L**1**′ entering the resonator **40**. The second circulated light WL**2** may propagate in a whispering gallery mode of a higher order, and for example, the second circulated light WL**2** may propagate in a second whispering gallery mode. The wavelength of the second harmonic component may correspond to ½ of the wavelength of the light L**1**′. The wavelengths of the light L**1**′ and the first circulated light WL**1** may be the same as each other and belong to a near-infrared region. Thus, the wavelength of the second circulated light WL**2** corresponding to the second harmonic component may belong to a visible light band. That is, the second circulated light WL**2** may be visible light. For example, when the wavelength of the light L**1**′ is about 1200 nm, the wavelength of the second circulated light WL**2** corresponding to the second harmonics may be about 600 nm.
(53) When effective refractive indices of the first circulated light WL**1** and the second circulated light WL**2** coincide with each other and resonant spectra thereof also coincide with each other in the resonator **40**, the second circulated light WL**2** may be radiated to the outside of the resonator **40** through the first decoupler **42**.
(54) FIG. **10** shows an example of such radiation.
(55) FIGS. **9** and **10** will be referred to together.
(56) Intensity distribution of the first circulated light WL**1** and intensity distribution of the second circulated light WL**2** seen in a cross-section perpendicular to the traveling direction of the first

circulated light WL**1** and the second circulated light WL**2** may decrease toward a center of the resonator **40**. The first circulated light WL**1** may be between the first decoupler **42** and the edge of the resonator **40**, but the intensity distribution thereof may end before the first decoupler **42**. That is, the first circulated light WL**1** may not reach the first decoupler **42**.

(57) On the other hand, the second circulated light WL**2** may be between the first decoupler **42** and the edge of the resonator **40**, but may be inward from the first circulated light WL**1**, and the intensity distribution of the second circulated light WL**2** may reach the first decoupler **42**. That is, the second circulated light WL**2** may reach the first decoupler **42**. The second circulated light WL**2** reaching the first decoupler **42** may be separated by the first decoupler **42** and radiated to the outside of the resonator **40**. That is, the second circulated light WL**2** may be diffracted by the first decoupler **42** and radiated to the outside of the resonator **40**. In an example, the first decoupler **42** may be patterned such that the second circulated light WL**2** radiated by the first decoupler **42** is radiated below the resonator **40**. Thus, in an operating process of the first thermal sensor **100**, visible light VL**1** radiated from a region of the resonator **40** where the first decoupler **42** is provided may be incident onto the image sensor **20**. When the visible light VL**1** is received by the image sensor **20** from the resonator **40**, it may mean that resonance occurs between the light L**1**′ introduced into the resonator **40** and the resonator **40** in the optical coupling region **90**. The wavelength of the first light L**1** radiated from the light source **80** may be known through a controller connected to the light source **80**, and thus the resonant wavelength of the resonator **40** may also be known.

(58) As the infrared light as an outside light is incident onto the top surface of the resonator **40**, the temperature of the resonator **40** may increase and the resonant wavelength of the resonator **40** may be changed. The wavelength of light radiated from the light source **80** may be swept in a range of possible resonant wavelengths of the resonator **40** using the controller. By a process of sweeping the wavelength of light radiated from the light source **80**, light having a wavelength corresponding to the changed resonant wavelength of the resonator **40** may be incident from the waveguide **70** to the resonator **40** and, as described above, the visible light VL**1** may be radiated to the image sensor **20** in the region of the resonator **40** where the first decoupler **42** is provided. Sweeping of the wavelength of the light radiated from the light source **80** and reception of visible light by the image sensor **20** may be performed in real time, such that the wavelength of the light L**1**′ introduced into the resonator **40** corresponding to the changed resonant wavelength of the resonator **40** may be known. That is, after the resonant wavelength of the resonator **40** is changed by incidence of the infrared light, the visible light radiated from the resonator **40** may be received and the changed resonant wavelength of the resonator **40** may be known. In other words, before and after infrared light is incident onto the top surface of the resonator **40**, the visible light VL**1** radiated from the resonator **40** may be received and the resonant wavelength of the resonator **40** for each case may be measured, such that the degree of movement of the resonant wavelength of the resonator **40**, i.e., the shift of the resonant wavelength thereof with respect to incidence of the infrared light to the resonator **40** may be known. The shift of the resonant wavelength of the resonator **40** may increase in proportional to an intensity of an outside light such as an infrared light incident onto the top surface of the resonator **40**. Thus, by measuring the shift of the resonant wavelength of the resonator **40**, the intensity of infrared light incident onto the top surface of the resonator **40** may be measured and a relative intensity of the infrared light may be known. As the infrared light is incident onto the top surface of the resonator **40**, the temperature of the resonator **40** may increase with the shift of the resonant wavelength of the resonator **40**. Thus, data about the degree of temperature change of the resonator **40** may be obtained from the shift of the resonant wavelength of the resonator **40**, and the temperature of the resonator **40** after incidence of infrared light may be known from the data.

(59) This case may be equally applied to each thermal sensor when a plurality of first thermal sensors **100** are provided.

(60) The resonator **40** may be positioned to correspond to or align with a plurality of pixels of the image sensor **20**. For example, the resonator **40** may be positioned correspond to or align with at least two pixels **20***b*. Thus, the visible light VL**1** radiated down from the first decoupler **42** of the resonator **40** may be received by the plurality of pixels **20***b* under the resonator **40**. As such, the visible light VL**1** radiated from the resonator **40** may be received by the image sensor **20**, and thus the resonator **40** and the image sensor **20** may be regarded as being optically coupled together.
(61) In an example, the first decoupler **42** of the resonator **40** may be provided at another position. FIG. **11** shows an example thereof.
(62) Referring to FIG. **11**, the resonator **40** may include a second decoupler **92** in place of the first decoupler at an edge of the resonator **40**. The second decoupler **92** may play the same role as the first decoupler **42**. The second decoupler **92** may protrude from an edge of the resonator **40** outwardly from the resonator **40**. When viewed from a plan view, the second decoupler **92** may face the outside of the resonator **40**, protrude from the edge of the resonator **40** in a direction perpendicular to the edge, and be a plurality of patterns separated from each other. The second decoupler **92** may be arranged along the edge of the resonator **40** and may be separated from each other. In an example, the second decoupler **92** may be a diffraction grating. In an example, a material of the second decoupler **92** may be the same as the material of the resonator **40**, without being limited thereto. The second decoupler **92** may be a result of a portion of the resonator **40** protruding outwardly from the resonator **40**, and thus the second decoupler **92** and the resonator **40** may be a single body having no physical boundary therebetween.
(63) In an example, the resonator **40** may omit the first decoupler **42** or the second decoupler **92**. Instead, the resonator **40** may have an irregular and rough texture along the periphery of the resonator **40**, which is labeled as a natural pattern **102**. The natural pattern **102** may arise during the formation process of the resonator **40**, rather than being added as a planned pattern, resulting non-flat or non-uniform surface irregularities. Thus, the form or characteristic of each instance of the natural pattern **102** may vary, and a distribution of these natural patterns **102** may not be consistent.
(64) In the optical coupling region **90** of the waveguide **70** and the resonator **40** of FIG. **1**, the waveguide **70** may not be linear. In an example, as shown in FIG. **13**, the waveguide **70** may be bent along a curved shape of the edge of the resonator **40** in the optical coupling region **90**. That is, in the optical coupling region **90**, the waveguide **70** may be curved.
(65) FIG. **14** is a graph of a harmonic generation efficiency of a thermal sensor according to an embodiment.
(66) In FIG. **14**, a y-axis may represent a wavelength of light (infrared laser) radiated from the light source **80** to the waveguide **70**, and an x-axis may represent relative detuning (mistuning) from the resonant wavelength of the resonator **40**.
(67) On the x-axis, no indicates an effective refractive index when (1) phase matching is made between the first circulated light WL**1** and the second circulated light WL**2**, that is, propagation phases of the first circulated light WL**1** and the second circulated light WL**2** are the same as each other and (2) the resonant spectrum of the first circulated light WL**1** and the second circulated light WL**2** coincides with the resonant spectrum of the resonator **40**. (1) and (2) may be conditions for generation of the second harmonics in the resonator **40**.
(68) Δn/n.sub.0 may indicate relative detuning from resonance in which Δn may indicate a change of an effective refractive index originating from an external factor, e.g., a temperature change. In other words, the lower x-axis may represent a resonance deviation measure of the resonator **40** from a state where the both conditions for harmonic generation (the same effective refractive indices, coincidence of the resonant spectra) are simultaneously satisfied.
(69) The upper x-axis may represent a temperature change of the resonator **40** (a temperature change due to a thermo-optic effect) due to external light (infrared light) incident onto the resonator **40** in which the temperature change may provide detuning for resonance of the resonator **40**. That is, the temperature change may cause the change of the resonant wavelength of the resonator **40**.

(70) In FIG. **14**, two dotted lines (C.sub.sh and C.sub.p) may indicate the change of the resonant wavelength (resonant circuit maxima) as a function of the refractive index change. Reference numeral C.sub.p may indicate a first resonant circuit for light radiated from the light source **80**. In C.sub.p, the subscript "p" may mean pumping.
(71) Reference numeral C.sub.sh may indicate a second resonant circuit for the second harmonics generated in the resonator **40**. In C.sub.sh, the subscript "sh" may indicate the second harmonics.
(72) Referring to the first and second resonant circuits (C.sub.p, C.sub.sh), the first and second resonant circuits (C.sub.p, C.sub.sh) intersect each other at a point where resonant detuning of the resonator **40** is 0. This may indicate coincidence of the resonant spectra (resonant wavelengths) of the first circulated light WL**1** and the second circulated light WL**2** generated in the resonator **40**. In this case, the first and second resonant circuits (C.sub.p, C.sub.sh) are the dependence of a power of a light wave stored in the resonator **40** on the wavelength thereof.
(73) When the wavelength of light introduced into the resonator **40** from the waveguide **70** is equal to the resonant wavelength of the resonator **40**, the power of the light wave stored in the resonator **40** may be maximum and drop off rapidly at both sides thereof.
(74) The first and second resonant circuits (C.sub.p, C.sub.sh) may be determined by drawing a cross section of a corresponding graph with a vertical line.
(75) For example, when a section line for a cross section is set by a line T=6 K for the temperature change of the resonator **40** and the dependence of color on the wavelength is illustrated, then two peaks (two resonant circuits), i.e., a strong value and a weak value may be obtained on such a graph.
(76) As the section line approaches the center, these peak values (the strong value and the weak value) may be close to each other, and may coincide with each other exactly in the center (where $\Delta n=0$).
(77) A harmonic generation efficiency in the resonator **40** may be determined by a product of the first and second resonant circuits (C.sub.p, C.sub.sh).
(78) When both conditions (1) and (2) for harmonic generation are satisfied and $\Delta n=0$, the generation spectrum may be a product of a square of the first resonant circuit C.sub.p and the second resonant circuit C.sub.sh.
(79) In the case of a very small temperature change of the resonator **40**, and hence a very weak detuning from the resonance in the resonator **40**, the sensitivity of the first thermal sensor **100** may be determined by a derivative of the resonant circuit of the generation efficiency with respect to the wavelength.
(80) For example, when the temperature of the resonator **40** by incidence of an outside infrared on the resonator **40** increases by 1 degree (upper x-axis), the shift of the resonant wavelength (the resonant shift) of the resonator **40** may be less than 0.1 nm (vertical y-axis), and the harmonic generation efficiency, i.e., the power of the visible signal detected by a photodetector may drop in 1/10.
(81) As a result, for the first thermal sensor **100** including the resonator **40** formed of a nonlinear optical material, even when a small amount of infrared light is incident onto the first thermal sensor **100** from the outside, the first thermal sensor **100** may react sensitively. In other words, even when the amount of infrared light incident onto the first thermal sensor **100** from the outside changes a little, the first thermal sensor **100** may react sensitively. This may mean improvement of sensitivity of the first thermal sensor **100** to infrared light.
(82) FIG. **15** shows a first thermal sensor array **200** according to an embodiment.
(83) While it is shown that the first thermal sensor array **200** includes nine thermal sensors for convenience, the first thermal sensor array **200** may include nine or less or nine or more thermal sensors **100′**. The first thermal array sensor **200** may include a plurality of thermal sensors **100′** to form a thermal image like an infrared image. Each thermal sensor **100′** included in the first thermal sensor array **200** may be the thermal sensor **100** according to the above-described embodiment. In

each thermal sensor **100′** of the thermal sensor array **200**, a thermally insulating bridge is omitted for convenience of illustration. The nine thermal sensors **100′** may be formed on one substrate **30**. In other words, the nine thermal sensors **100′** may share one substrate **30**.
(84) The thermal sensor array **200** may include one light source **80** and one waveguide **150** shared by all thermal sensors **100′**. In an example, the waveguide **150** may be the waveguide **70** described with reference to FIG. **1**. A side of the waveguide **150** may be connected to the light source **80** such that light (e.g., laser light) radiated from the light source **80** may enter the waveguide **150**. The waveguide **150** may be arranged close to all thermal sensors **100′**. A region where the waveguide **150** and each thermal sensor **100′** are close to each other may be an optical coupling region. That is, the waveguide **150** may be arranged to form optical coupling with all thermal sensors **100′**.
(85) FIG. **16** shows a second thermal sensor array **300** according to an embodiment. A part that is different from the first thermal sensor array **200** of FIG. **15** will be described. The same reference numeral as that described above indicates the same member and a description thereof will be omitted.
(86) Referring to FIG. **16**, the number, configuration, arrangement and layout of the plurality of thermal sensors **100′** included in the second thermal sensor array **300** may be the same as those of the first thermal sensor array **200**. However, the second thermal sensor array **300** may include a plurality of waveguides **160***a*, **160***b*, **160***c*, and **160***d* that are separated from one another. Moreover, the second thermal sensor array **300** may include a splitter **86** at an interconnection point of the plurality of waveguides **160***a* to **160***d*. The splitter **86** may be an example of a light splitter or a light distributor that divides light supplied through the first waveguide **160***a* into a plurality of different paths. The first waveguide **160***a* may be provided between the light source **80** and the splitter **86**. One of opposite ends of the first waveguide **160***a* may be directly or optically connected to the light source **80**. The other side of the opposite ends of the first waveguide **160***a* may be directly or optically connected to the splitter **86**. The splitter **86** may be arranged between the first waveguide **160***a* and the second to fourth waveguides **160***b* to **160***d*. One sides of the second to fourth waveguides **160***b* to **160***d* may be directly or optically connected to the splitter **86**. The second waveguide **160***b* may be arranged to correspond to a first column of the second thermal sensor array **300** (the first column of the second thermal sensor array **300** from the left). That is, the second waveguide **160***b* may be arranged to be shared among the thermal sensors **100′** of the first column. An arrangement relationship between the second waveguide **160***b* and the thermal sensors **100′** of the first column may be the same as that between the waveguide **150** of the first thermal sensor array **200** and the thermal sensors **100′**. The third waveguide **160***c* may be arranged to correspond to a second column (the second column of the second thermal sensor array **300** from the left). An arrangement relationship between the third waveguide **160***c* and the thermal sensors **100′** of the second column may be the same as that between the second waveguide **160***b* and the thermal sensors **100′** of the first column. The third waveguide **160***c* may be arranged in parallel to the second waveguide **160***b* with the thermal sensors **100′** of the first column therebetween. The fourth waveguide **160***d* may be arranged to correspond to a third column of the second thermal sensor array **300** (the third column of the second thermal sensor array **300** from the left or the first column from the right). A corresponding relationship or arrangement relationship between the fourth waveguide **160***d* and the thermal sensors **100′** of the third column may be the same as that between the second waveguide **160***b* and the thermal sensors **100′** of the first column. The fourth waveguide **160***d* may be parallel to the third waveguide **160***c* with the thermal sensors **100′** of the second column therebetween.
(87) Light transmitted from the light source **80** to the splitter **86** through the first waveguide **160***a* may be split as many as the number of waveguides **160***b* to **160***d* connected to the splitter **86** except for the first waveguide **160***a*. For FIG. **16**, the light transmitted to the splitter **86** through the first waveguide **160***a* may be split into three light rays having different propagation paths at the same time. The divided three light rays each may enter the second to fourth waveguides **160***b*, **160***c*, and

**160***d* at the same time. The first to fourth waveguides **160***a* to **160***d* may have the same material and cross-sectional configuration. Thus, light rays propagating through the second to fourth waveguides **160***b* to **160***d* may have the same phase and intensity.
(88) In an example, the second to fourth waveguides **160***b* to **160***d* may be separately connected to the light source **80** through different paths. In an example, the second thermal sensor array **300** may include a plurality of light sources that are synchronized with each other and a plurality of splitters, and in this case, the number of splitters may be equal to the number of light sources.
(89) Δn operation of one thermal sensor **100** described above may be equally applied to each thermal sensor **100′** of the first and second thermal sensor arrays **200** and **300** shown in FIGS. **15** and **16**. Thus, by sensing visible light radiated through a visible light radiation region of the resonator **40** of each thermal sensor **100′** of the arrays **200** and **300**, a shift of the resonant wavelength of the resonator **40** of each thermal sensor **100′** may be known, from which a temperature change of the resonator **40** of each thermal sensor **100′** and an intensity or relative intensity of infrared light incident onto the resonator **40** may be known. As a result, by using the first and second thermal sensor arrays **200** and **300**, a temperature distribution and/or intensity distribution of light (e.g., infrared light) incident onto the first and second thermal sensor arrays **200** and **300** may be known on the first and second thermal sensor arrays **200** and **300**. The temperature distribution or intensity distribution may correspond to a thermal image or infrared image of an object incident onto the thermal sensor arrays **200** and **300**. The temperature distribution or intensity distribution may be stored as data which may then be transmitted to a display device, such that the thermal image or infrared image may be seen through the display device. In an example, the display device may include a fixed display device regarded as being substantially fixed, and a display device portable by a person or a vehicle. In an example, the first and second thermal sensor arrays **200** and **300** may be components provided to sense infrared light in the display device.
(90) FIG. **17** is a perspective view of two rows and two columns selected from the first thermal sensor array **200** of FIG. **15** or the second thermal sensor array **300** of FIG. **16**.
(91) Referring to FIG. **17**, in each of the thermal sensor arrays **200** and **300**, one resonator **40** may correspond to a plurality of pixels of the image sensor **20** thereunder. In each of the thermal sensor arrays **200** and **300**, one thermal sensor **100′** may correspond to one of pixels of a thermal image for an object (an external object) sensed by each of the thermal sensor arrays **200** and **300**. Thus, by reducing a size of the thermal sensor **100′** of each of the thermal sensor arrays **200** and **300**, the integration of each of the thermal sensor arrays **200** and **300** may be increased and the resolution of the thermal image of the object sensed by each of the thermal sensor arrays **200** and **300** may be increased. Each of the thermal sensor arrays **200** and **300** senses a thermal image by receiving visible light generated from the resonator **40** through the image sensor **20** when the wavelength of light supplied from the light source **80** corresponds to the resonant wavelength of the resonator **40**, and correspondence of the resonant wavelength and corresponding radiation of visible light from the resonator **40** may be maintained even when the size of the thermal sensor **100′** is reduced. In other words, regardless of size reduction of the thermal sensor **100′**, visible light radiation corresponding to the resonant wavelength may occur normally in each of the thermal sensor arrays **200** and **300**.
(92) Thus, when the thermal sensor array **200** or **300** according to an embodiment is used, the integration of the thermal sensor array **200** or **300** may be improved while using a CMOS visible light image sensor.
(93) The thermal sensor or thermal sensor array according to an embodiment described above may be applied to a thermal imaging camera, and may also be used in a device for capturing an image or a photo in a limited visibility or low light condition.
(94) FIG. **18** shows a thermal imaging camera **180** as an example of an electronic device configured to capture images.

(95) Referring to FIG. **18**, the thermal imaging camera **180** may include a thermal sensor **182** and an infrared optical system **184**. The thermal sensor **182** may include the thermal sensor **100** described above or the thermal sensor array **200** or **300**. In an example, the infrared optical system **184** may form a thermal image **190**, i.e., an infrared image (e.g., an MWIR image). The thermal sensor **182** and the infrared optical system **184** may be separated from each other by a second distance D**2**. In an example, the second distance D**2** may correspond to a focal length of the infrared optical system **184**. Thus, the thermal sensor **182** may be located in a focal plane of the infrared optical system **184**. Accordingly, a thermal image **190** formed by the infrared optical system **184** may be imaged on the thermal sensor **182**. In other words, a distribution map of infrared light incident onto the camera **180** from an object **188** outside the camera **180** may be displayed on the thermal sensor **182** by the infrared optical system **184**. That is, the thermal image **190** of the object **188** may be transmitted to the thermal sensor **182** by the optical system **184**. The thermal sensor **182** may include the resonator layer RL**1**, the image sensor **20**, and a controller **186** connected to the resonator layer RL**1** and the image sensor **20**. The controller **186** may be connected to the image sensor **20** through a control terminal. The controller **186** may be connected to the light source **80** and control a light radiation operation of the light source **80** to change the wavelength of light radiated from the light source **80**. The wavelength change operation of the light source **80** may be controlled by the controller **186** to correspond to (interact with) the resonance of the resonator **40** of the resonator layer RL**1**. As the controller **186** is connected to the resonator layer RL**1** and the image sensor **20** at the same time, the wavelength change of the light source **80** and the detection of visible light radiated from a visible light radiation region of the resonator layer RL**1** may be made in real time, thereby measuring the resonant wavelength of the resonator **40** in real time. The controller **186** may be implemented as a processor and/or an analog control circuit.
(96) The resonator layer RL**1** may be arranged to face the optical system **184**. The resonator layer RL**1** may be located in the focal plane of the optical system **184**.
(97) The thermal image **190** may be imaged on the thermal sensor **182**, and visible light may be radiated to the image sensor **20** from the resonator **40** through the shift of the resonant wavelength of the resonator **40** of the thermal sensor **182** and the wavelength change operation of the light source **80** corresponding thereto. The image sensor **20** may receive such light and form a visible light image pattern corresponding to the thermal image **190**. Δn image pattern formed by the image sensor **20** may include information (data) about the resonant frequency shift of the resonator **40**, and thus may be used as intermediate data for calculating a temperature change of the resonator **40** and the intensity of infrared light incident onto the resonator **40** as the thermal image **190** is formed on the resonator layer RL**1**.
(98) As the surface temperature of the object **188** increases, the intensity of the infrared light incident onto the resonator **40** may increase, such that the surface temperature of the object **188** may be known by measuring the intensity of the infrared light incident onto the resonator **40**. That is, information about distribution of the surface temperature of the object **188** may be known from an infrared intensity distribution map of the thermal image **190**.
(99) For the thermal image **190** of the object **188** formed by the optical system **184**, the thermal sensor **182** shows an infrared intensity distribution corresponding thereto on the thermal sensor array. Such an infrared intensity distribution may not transmit any information without the optical system **184**, and a thermal image by the optical system **184** may correspond to an infrared image of the object **188**.
(100) When the thermal image **190** is incident onto the thermal sensor **182**, a shift value of the resonant wavelength of each thermal sensor **100′** of the thermal sensor array due to incidence of the thermal image **190** may be measured by the controller **186**, and the intensity of the infrared light incident onto the thermal sensor **100′** may be calculated by the measured shift value of the resonant wavelength, such that the thermal sensor **182** may determine the thermal image **190** as the infrared image of the object **188**.

(101) The thermal imaging camera **180** may be a still image camera or a video camera.
(102) The thermal imaging camera **180** may include an electronic device for processing or converting data generated by an operation of each element.
(103) In an example, when it is necessary to transmit the thermal image **190** determined by the thermal sensor **182** to a display unit in the camera **180** or a display device outside the thermal imaging camera **180**, the electronic device may include a video signal according to a known standard procedure.
(104) In an example, a data array obtained from the image sensor **20** may be encoded and then transmitted to an internal or external display through an analog or digital interface. When an image obtained from the image sensor **20** needs to be stored, data about the obtained image may be recorded on a memory.
(105) In an example, a thermal image or an infrared image obtained from the thermal sensor **100** or the thermal sensor array **200** or **300** according to an embodiment described above may be superimposed onto a visible image (e.g., a visible image obtained through a mobile phone) obtained from a visible image sensor. By doing so, a clear image may be obtained in real time in a poor environment such as a low light condition.
(106) To this end, the thermal imaging camera **180** may include a separate visible light camera for capturing a visible image. On the other hand, a thermal imaging camera may be provided in a visible light camera for capturing a color or black/white image.
(107) In this case, the thermal imaging camera and the visible light camera may be arranged such that the thermal image obtained from the thermal imaging camera is superimposed onto the visible image in real time.
(108) Besides, superimposition between the thermal image and the visible image may be used for various purposes, for example, a night-time driving vehicle, and may be used in the medical field for determining a disease of an individual organ and a temperature thereof as well as for measuring vein biometry, and in everyday life, it may be used, for example, to manufacture a frame structure of a house to control heat dissipation and find where cold air is blowing in a window frame by using a smartphone.
(109) FIG. **19** is a block diagram of schematic configuration of an electronic apparatus according to an embodiment.
(110) Referring to FIG. **19**, in a network environment **2200**, an electronic apparatus **2201** may communicate with another electronic apparatus **2202** through a first network **2298** (a short-range wireless communication network, etc.) or communicate with another electronic apparatus **2204** and/or a server **2208** through a second network **2299** (a long-range wireless communication network, etc.). The electronic apparatus **2201** may communicate with the electronic apparatus **2204** via the server **2208**. The electronic apparatus **2201** may include a processor **2220**, a memory **2230**, an input device **2250**, a sound output device **2255**, a display device **2260**, an audio module **2270**, a sensor module **2210**, an interface **2277**, a haptic module **2279**, a camera module **2280**, a power management module **2288**, a battery **2289**, a communication module **2290**, a subscriber identification module **2296**, and/or an antenna module **2297**. In the electronic apparatus **2201**, some (the display device **2260**, etc.) of the components may be omitted or another component may be added. Some of the components may be configured as one integrated circuit. For example, a fingerprint sensor **2211**, an iris sensor, an illumination sensor, etc., of the sensor module **2210** may be implemented in a form embedded in the display device **2260** (a display, etc.).
(111) The processor **2220** may control one or more components (hardware, software components, etc.) of the electronic apparatus **2201** connected to the processor **2220** by executing software (the program **2240**, etc.), and may perform various data processes or operations. As a part of the data processes or operations, the processor **2220** may load a command and/or data received from another component (the sensor module **2210**, the communication module **2290**, etc.) to a volatile memory **2232**, may process the command and/or data stored in the volatile memory **2232**, and may

store result data in a non-volatile memory **2234**. The processor **2220** may include a main processor **2221** (a central processing unit, an application processor, etc.) and an auxiliary processor **2223** (a graphics processor unit (GPU), an image signal processor, a sensor hub processor, a communication processor, etc.) that may operate independently of or along with the main processor **2221**. The auxiliary processor **2223** may use less power than that of the main processor **2221**, and may perform specified functions.

(112) The auxiliary processor **2223**, on behalf of the main processor **2221** while the main processor **2221** is in an inactive state (a sleep state), or along with the main processor **2221** while the main processor **2221** is in an active state (an application executed state), may control functions and/or states related to some (the display device **2260**, the sensor module **2210**, the communication module **2290**, etc.) of the components of the electronic apparatus **2201**. The auxiliary processor **2223** (the image signal processor, the communication processor, etc.) may be implemented as a part of another component (the camera module **2280**, the communication module **2290**, etc.) that is functionally related thereto.

(113) The memory **2230** may store various data required by the components (the processor **2220**, the sensor module **2276**, etc.) of the electronic apparatus **2201**. The data may include, for example, software (the program **2240**, etc.) and input data and/or output data about commands related thereto. The memory **2230** may include the volatile memory **2232** or the non-volatile memory **2234**. The non-volatile memory **2234** may include an internal memory **2236** and an external memory **2238**. The program **2240** may be stored as software in the memory **2230**, and may include an operating system **2242**, middleware **2244**, and/or an application **2246**.

(114) The input device **2250** may receive commands and/or data to be used in the components (the processor **2220**, etc.) of the electronic apparatus **2201**, from the outside (a user, etc.) of the electronic apparatus **2201**. The input device **2250** may include a microphone, a mouse, a keyboard, and/or a digital pen (a stylus pen).

(115) The sound output device **2255** may output a sound signal to the outside of the electronic apparatus **2201**. The sound output device **2255** may include a speaker and/or a receiver. The speaker may be used for a general purpose such as multimedia reproduction or record play, and the receiver may be used to receive a call. The receiver may be coupled as a part of the speaker or may be implemented as an independent separate device.

(116) The display device **2260** may provide visual information to the outside of the electronic apparatus **2201**. The display device **2260** may include a display, a hologram device, or a projector, and a control circuit for controlling the corresponding device. The display device **2260** may include a touch circuitry configured to sense a touch, and/or a sensor circuit (a pressure sensor, etc.) that is configured to measure a strength of a force generated by the touch.

(117) The audio module **2270** may convert sound into an electrical signal or vice versa. The audio module **2270** may acquire sound through the input device **2250**, or may output sound via the sound output device **2255** and/or a speaker and/or a headphone of another electronic device (the electronic apparatus **2202**, etc.) connected directly or wirelessly to the electronic apparatus **2201**.

(118) The sensor module **2210** may sense an operating state (power, temperature, etc.) of the electronic apparatus **2201**, or an outer environmental state (a user state, etc.), and may generate an electrical signal and/or a data value corresponding to the sensed state. The sensor module **2210** may include the fingerprint sensor **2211**, an acceleration sensor **2212**, a position sensor **2213**, a three-dimensional (3D) sensor **2214**, etc., and may also include an iris sensor, a gyro sensor, a pressure sensor, a magnetic sensor, a grip sensor, a proximity sensor, a color sensor, an infrared (IR) sensor, a biometric sensor, a temperature sensor, a humidity sensor, and/or an illumination sensor.

(119) The 3D sensor **2214** may sense a shape, a motion, etc., of a subject by emitting or radiating certain light to the subject and analyzing the light reflected from the subject, and may include a meta-optical element.

(120) The interface **2277** may support one or more designated protocols that may be used in order

for the electronic apparatus **2201** to be directly or wirelessly connected to another electronic device (the electronic apparatus **2202**, etc.). The interface **2277** may include a high-definition multimedia interface (HDMI), a universal serial bus (USB) interface, a secure digital (SD) card interface, and/or an audio interface.

(121) The connection terminal **2278** may include a connector by which the electronic apparatus **2201** may be physically connected to another electronic apparatus (the electronic apparatus **2202**, etc.). The connection terminal **2278** may include an HDMI connector, a USB connector, an SD card connector, and/or an audio connector (a headphone connector, etc.).

(122) The haptic module **2279** may convert the electrical signal into a mechanical stimulation (vibration, motion, etc.) or an electric stimulation that the user may sense through a tactile or motion sensation. The haptic module **2279** may include a motor, a piezoelectric device, and/or an electric stimulus device.

(123) The camera module **2280** may capture a still image and a moving image. The camera module **2280** may include a lens assembly including one or more lenses, image sensors, image signal processors, and/or flashes. The lens assembly included in the camera module **2280** may collect light emitted from an object that is an object to be captured. In an example, the camera module **2280** may be provided to capture at least one of a visible image and a thermal image (or an infrared image) of the object. In an example, the camera module **2280** may include a thermal sensor, a thermal sensor array, and/or the thermal imaging camera **180** according to the above-described embodiment to capture the infrared image of the object. In an example, the image signal processor included in the camera module **2280** may perform an operation of superimposing the infrared image obtained by the thermal imaging camera **180** onto the visible image.

(124) The power management module **2288** may manage power supplied to the electronic apparatus **2201**. The power management module **2288** may be implemented as a part of a power management integrated circuit (PMIC).

(125) The battery **2289** may supply electric power to components of the electronic apparatus **2201**. The battery **2289** may include a primary battery that is not rechargeable, a secondary battery that is rechargeable, and/or a fuel cell.

(126) The communication module **2290** may support establishment of a direct (wired) communication channel and/or a wireless communication channel between the electronic apparatus **2201** and another electronic apparatus (the electronic apparatus **2202**, the electronic apparatus **2204**, the server **2208**, etc.), and execution of communication through the established communication channel. The communication module **2290** may operate independently of the processor **2220** (the application processor, etc.), and may include one or more communication processors that support the direct communication and/or the wireless communication. The communication module **2290** may include a wireless communication module **2292** (a cellular communication module, a short-range wireless communication module, a global navigation satellite system (GNSS) communication module) and/or a wired communication module **2294** (a local area network (LAN) communication module, a power line communication module, etc.). From among the communication modules, a corresponding communication module may communicate with another electronic device via a first network **2298** (a short-range communication network such as Bluetooth, Wireless Fidelity (WiFi) Direct, or Infrared Data Association (IrDA)) or a second network **2299** (a long-range communication network such as a cellular network, Internet, or a computer network (LAN, a wide area network (WAN), etc.)). Such various kinds of communication modules may be integrated as one component (a single chip, etc.) or may be implemented as a plurality of components (a plurality of chips) separately from one another. The wireless communication module **2292** may identify and authenticate the electronic apparatus **2201** in a communication network such as the first network **2298** and/or the second network **2299** by using subscriber information (an international mobile subscriber identifier (IMSI), etc.) stored in the subscriber identification module **2296**.

(127) The antenna module **2297** may transmit or receive a signal and/or power to/from outside (another electronic apparatus, etc.). An antenna may include a radiator formed as a conductive pattern formed on a substrate (a printed circuit board (PCB), etc.). The antenna module **2297** may include one or more antennas. When the antenna module **2297** includes a plurality of antennas, an antenna that is suitable for a communication scheme used in the communication network such as the first network **2298** and/or the second network **2299** may be selected by the communication module **2290** from among the plurality of antennas. The signal and/or the power may be transmitted between the communication module **2290** and another electronic apparatus via the selected antenna. Another component (a radio frequency integrated circuit (RFIC), etc.) other than the antenna may be included as a part of the antenna module **2297**.
(128) Some of the components may be connected to one another via a communication scheme between peripheral devices (a bus, general purpose input and output (GPIO), a serial peripheral interface (SPI), a mobile industry processor interface (MIPI), etc.) and may exchange signals (commands, data, etc.).
(129) The command or data may be transmitted or received between the electronic apparatus **2201** and the external electronic apparatus **2204** via the server **2208** connected to the second network **2299**. Other electronic apparatuses **2202** and **2204** may be devices of types that are the same as or different from the electronic apparatus **2201**. All or some of operations executed in the electronic apparatus **2201** may be executed in one or more apparatuses among the other electronic apparatuses **2202**, **2204**, and **2208**. For example, when the electronic apparatus **2201** has to perform a certain function or service, the electronic apparatus **2201** may request one or more other electronic apparatuses to perform some or entire function or service, instead of executing the function or service by itself. One or more electronic apparatuses receiving the request execute an additional function or service related to the request and may transfer a result of the execution to the electronic apparatus **2201**. For this end, cloud computing, distributed computing, and/or a client-server computing technique may be used.
(130) Although many matters are specifically described in the foregoing description, they should be interpreted as an example of an embodiment, rather than limiting the scope of the disclosure. Therefore, the scope of the disclosure should not be determined by the described embodiments, but by the technical spirit set forth in the claims.
(131) The disclosed thermal sensor may use visible light generated in the microresonator to sense infrared light. The visible light is received using the CMOS image sensor optically coupled with the microresonator. That is, the disclosed thermal sensor may be compatible with the CMOS technology. Thus, by using the disclosed thermal sensor, the thermal sensor structure is not complex when compared to an existing case where the thermal sensor is electrically connected, and a manufacturing process is relatively simple, thus lowering a manufacturing cost.
(132) Moreover, when infrared light is incident onto the microresonator, visible light may be generated in the microresonator correspondingly, and the size of one microresonator may be equal to or greater than the size of one pixel of an image sensor under the microresonator in spite of size reduction of the microresonator, such that the visible light may be still radiated in the microresonator and the radiated visible light may be sensed by the image sensor under the resonator. As a result, the visible light radiated from the microresonator may not be related to the size of the microresonator, such that the disclosed thermal sensor may be implemented with a compact thermal sensor. In other words, by using the disclosed thermal sensor, the integration of the thermal sensor may be improved.
(133) Moreover, the visible light radiated from the microresonator of the disclosed thermal sensor may be radiated when harmonics (visible light) generated in the microresonator satisfy a specific condition in relation to the resonant wavelength of the microresonator, and thus the intensity of the visible light may sharply decrease even with a slight change of the resonant wavelength of the microresonator. In other words, the intensity of the visible light radiated from the microresonator

may greatly change with a small change of the resonant wavelength of the microresonator.
(134) In a sense that the resonant wavelength of the microresonator changes when the infrared light is incident onto the microresonator, a large change in the intensity of the visible light radiated from the microresonator with a very small change in the resonant wavelength of the microresonator may mean that the infrared sensitivity of the disclosed thermal sensor is very high.
(135) It should be understood that embodiments described herein should be considered in a descriptive sense only and not for purposes of limitation. Descriptions of features or aspects within each embodiment should typically be considered as available for other similar features or aspects in other embodiments. While one or more embodiments have been described with reference to the figures, it will be understood by those of ordinary skill in the art that various changes in form and details may be made therein without departing from the spirit and scope as defined by the following claims.

## Claims

1. A thermal sensor comprising: a first region onto which first infrared light is incident; a visible light radiation region configured to emit visible light that is generated in response to the first infrared light being incident on the first region; a second region onto which second infrared light is incident; and an image sensor configured to receive the visible light emitted from the visible light radiation region, wherein each of the first region, the second region, and the visible light radiation region comprises a nonlinear optical material.
2. The thermal sensor of claim 1, wherein the first region, the second region, and the visible light radiation region are connected to one another.
3. The thermal sensor of claim 1, wherein the visible light radiation region is in the second region.
4. The thermal sensor of claim 3, wherein the visible light radiation region is located between an edge of the second region and a center of the second region, and surrounds the center.
5. The thermal sensor of claim 1, wherein the visible light radiation region is in an outer boundary of the second region.
6. The thermal sensor of claim 1, wherein the visible light includes harmonics generated in response to the first infrared light being incident on the first region.
7. The thermal sensor of claim 6, wherein the visible light radiation region comprises a decoupler arranged at a harmonic resonance distance where the harmonics are reached.
8. The thermal sensor of claim 7, wherein the decoupler comprises a diffraction grating.
9. The thermal sensor of claim 1, further comprising: a resonator optically coupled to the image sensor; a waveguide configured to form optical coupling between a part of the waveguide and the resonator; a light source provided to emit the first infrared light into the waveguide; and a controller configured to change a wavelength of light emitted from the light source to correspond to a change of a resonant wavelength of the resonator, wherein the resonator comprises a top surface and a side surface, and a region of the side surface of the resonator, which forms the optical coupling with the waveguide, corresponds to the first region, the top surface of the resonator corresponds to the second region, and the visible light radiation region is a partial region of the top surface.
10. The thermal sensor of claim 9, wherein a portion of the waveguide, optically coupled to the resonator, is linear or curved.
11. The thermal sensor of claim 9, wherein the waveguide comprises a non-linear optical material.
12. The thermal sensor of claim 9, further comprising: a transparent substrate comprising a through-hole; and a thermally insulating bridge provided to connect the transparent substrate to the resonator and support the resonator, wherein the resonator is located inside the through-hole and does not directly contact the substrate, and a part of the through-hole except for the resonator and the thermally insulating bridge, is filled with a thermally insulating layer.

13. The thermal sensor of claim 1, wherein the image sensor comprises a complementary metal oxide semiconductor (CMOS) image sensor.
14. The thermal sensor of claim 1, wherein the nonlinear optical material comprises a silicon nitride.
15. The thermal sensor of claim 12, wherein a plurality of through-holes are provided to be separated from each other in the transparent substrate, the resonator, the thermally insulating bridge, and the thermally insulating layer are provided in each of the plurality of through-holes, and the waveguide is shared by the resonators provided in the plurality of through-holes.
16. The thermal sensor of claim 15, wherein the plurality of through-holes are arranged to form a matrix, an optical splitter is further provided between the light source and the plurality of through-holes, the waveguide comprises a plurality of waveguides, and one of the plurality of waveguides is provided between the light source and the optical splitter, and the other of the plurality of waveguides are arranged in a one-to-one correspondence with rows or columns of the plurality of through-holes.
17. A thermal imaging camera comprising: an infrared optical system configured to form a thermal image of an object; and a thermal sensor arranged at a focal distance of the infrared optical system on which the thermal image is imaged, wherein the thermal sensor comprises: a first region onto which first infrared light is incident; a visible light radiation region configured to emit visible light that is generated in response to the first infrared light being incident on the first region; a second region onto which the thermal image is incident; and an image sensor provided at a position to receive the visible light emitted from the visible light radiation region, and each of the first region, the second region, and the visible light radiation region comprises a nonlinear optical material.
18. The thermal imaging camera of claim 17, further comprising: a resonator optically coupled to the image sensor and comprising the nonlinear optical material; a waveguide configured to form optical coupling between a part of the waveguide and the resonator; a light source provided to emit the first infrared light into the waveguide; and a controller provided to change a wavelength of light emitted from the light source to correspond to a change of a resonant wavelength of the resonator and connected to the image sensor, wherein the resonator comprises a top surface and a side surface, and a region of the side surface of the resonator, which forms optical coupling with the waveguide, corresponds to the first region, the top surface of the resonator corresponds to the second region, and the visible light radiation region is a partial region of the top surface.
19. An electronic apparatus comprising the thermal sensor of claim 1.
20. An operating method of a thermal sensor, the operating method comprising: receiving visible light emitted from a resonator of the thermal sensor before shifting of a resonant wavelength of the resonator to obtain first data about a first visible image of the resonator; receiving visible light emitted from the resonator after shifting of the resonant wavelength of the resonator due to incidence of external infrared light onto the resonator to obtain second data about a second visible image of the resonator; obtaining, based on the first data and the second data, third data about shifting of the resonant wavelength of the resonator due to the incidence of the external infrared light; and determine, based on the third data, a temperature of the resonator and an intensity of the external infrared light on the resonator due to the incidence of the external infrared light.