US 20220413135A1

(19) **United States**
(12) **Patent Application Publication**
Gorman et al.

(10) **Pub. No.: US 2022/0413135 A1**
(43) **Pub. Date: Dec. 29, 2022**

(54) **OPTOMECHANICAL ULTRASOUND DETECTOR AND PERFORMING ULTRASOUND IMAGING**

(71) Applicant: **Government of the United States of America, as represented by the Secretary of Commerce**, Gaithersburg, MD (US)

(72) Inventors: **Jason John Gorman**, Silver Spring, MD (US); **Thomas Warren LeBrun**, Washington, DC (US); **David Alexander Long**, Bethesda, MD (US)

(21) Appl. No.: **17/853,106**

(22) Filed: **Jun. 29, 2022**

Related U.S. Application Data

(60) Provisional application No. 63/216,079, filed on Jun. 29, 2021.

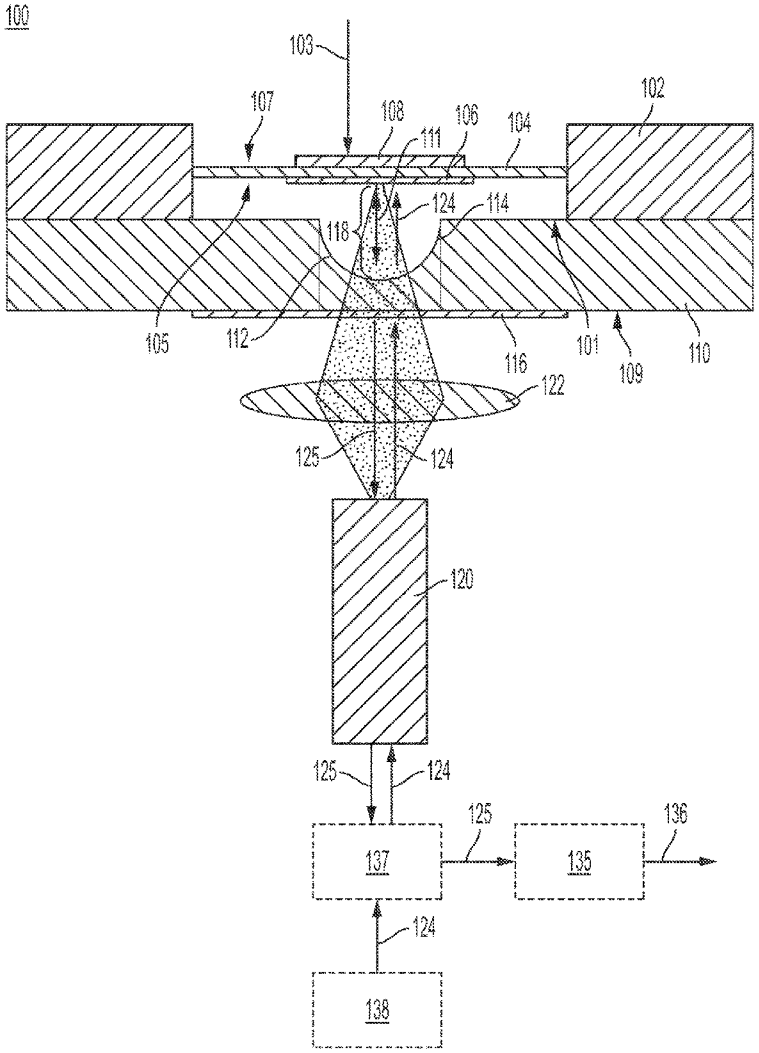
Publication Classification

(51) **Int. Cl.**
G01S 15/89 (2006.01)
G01S 7/52 (2006.01)

(52) **U.S. Cl.**
CPC ***G01S 15/8968*** (2013.01); ***G01S 15/8915*** (2013.01); ***G01S 7/52023*** (2013.01); ***G01S 7/52079*** (2013.01)

(57) **ABSTRACT**

An optomechanical ultrasound detector includes: a micromirror substrate; a mechanical resonator that receives ultrasound waves, oscillates at resonator frequency f_r, changes cavity length L_c, and produces intra-cavity light; and an optical microcavity between the micromirror substrate and the mechanical resonator with cavity length Lc and cavity resonance frequency f_c formed by the mechanical resonator and the micromirror substrate, such that the micromirror substrate produces cavity output light from the intra-cavity light, wherein the cavity output light optically encodes information about the ultrasound waves received by the mechanical resonator.



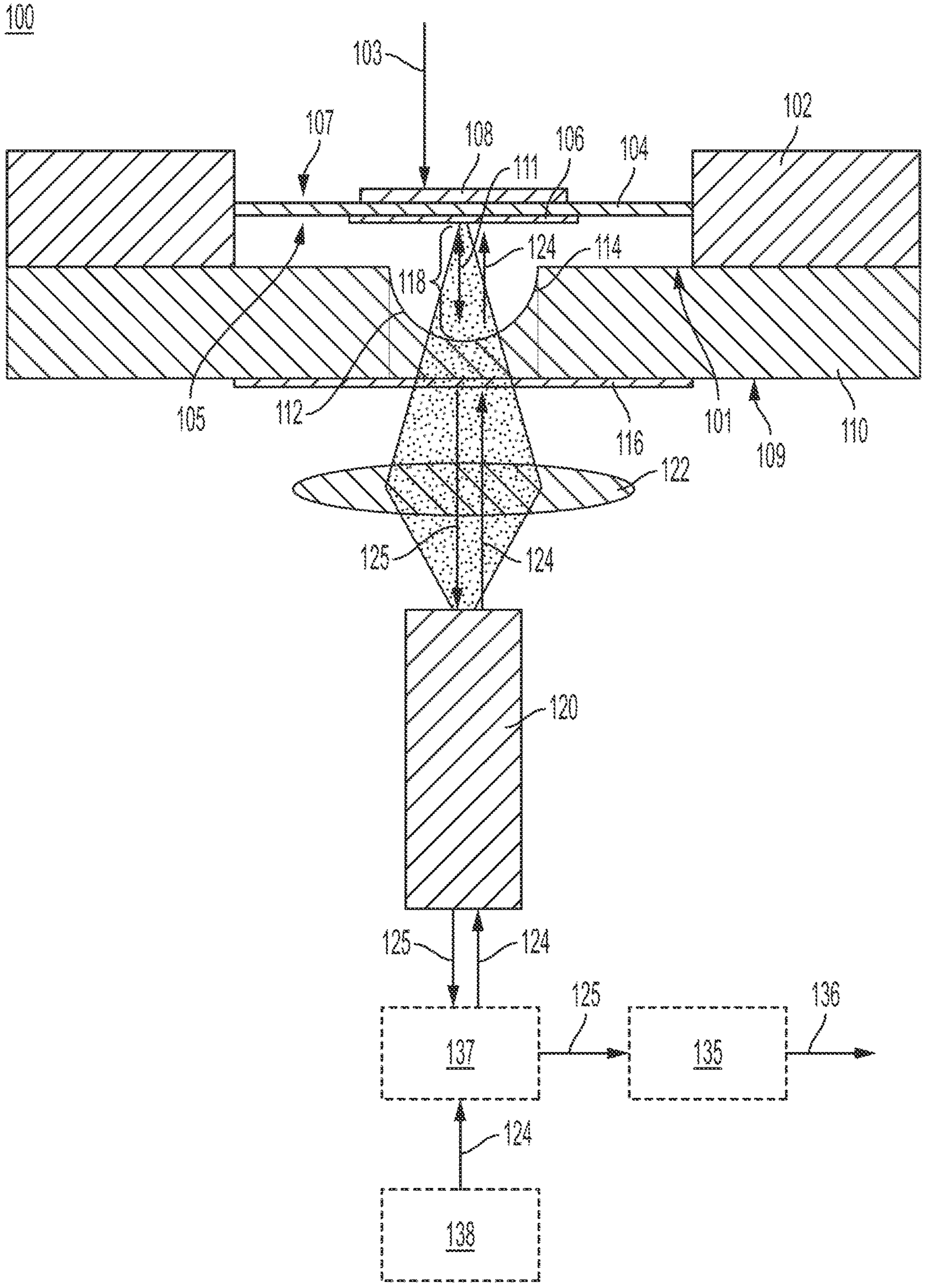

100
103
107
108
111
106
104
102
124
114
118
105
112
116
101
109
110
122
125
124
120
125
124
125
136
137
135
124
138

FIG. 1

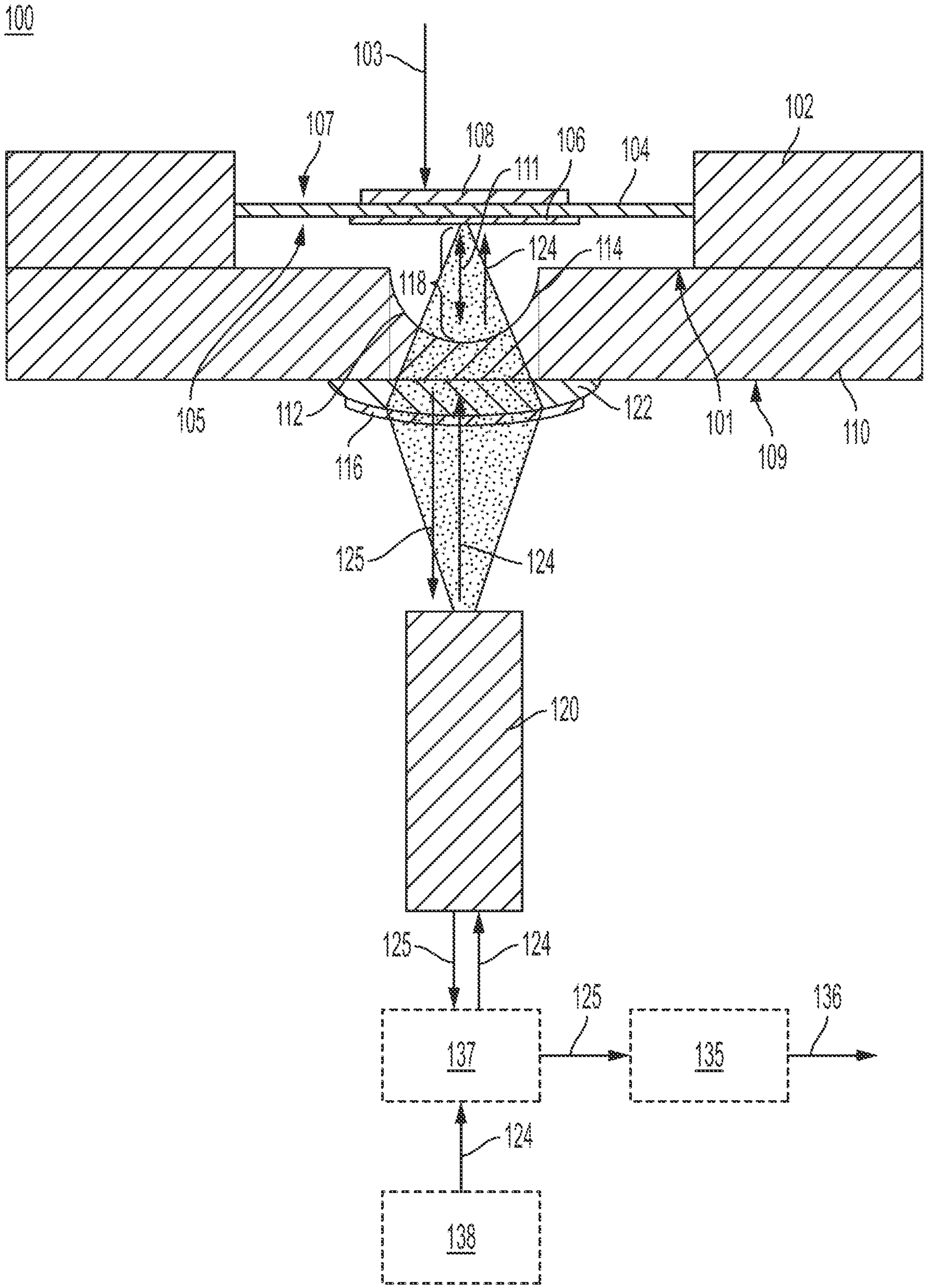

100
103
107
108
111
106
104
102
124
114
118
105
112
116
122
101
109
110
125
124
120
125
124
125
136
137
135
124
138

FIG. 2

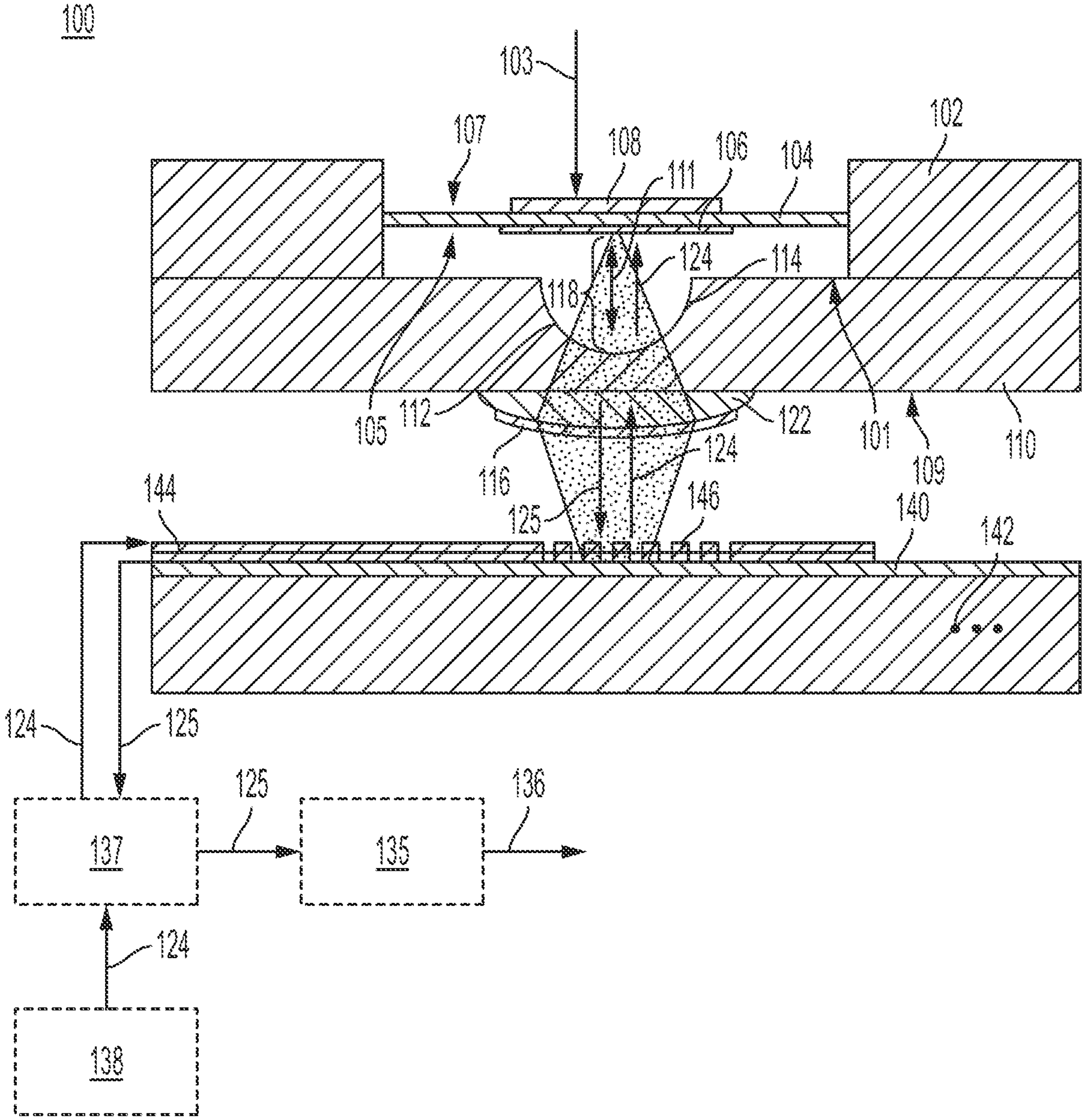

100
103
107
108
111
106
104
102
124
114
118
105
112
122
101
109
110
116
124
125
146
144
140
142
124
125
137
125
135
136
124
138

FIG. 3

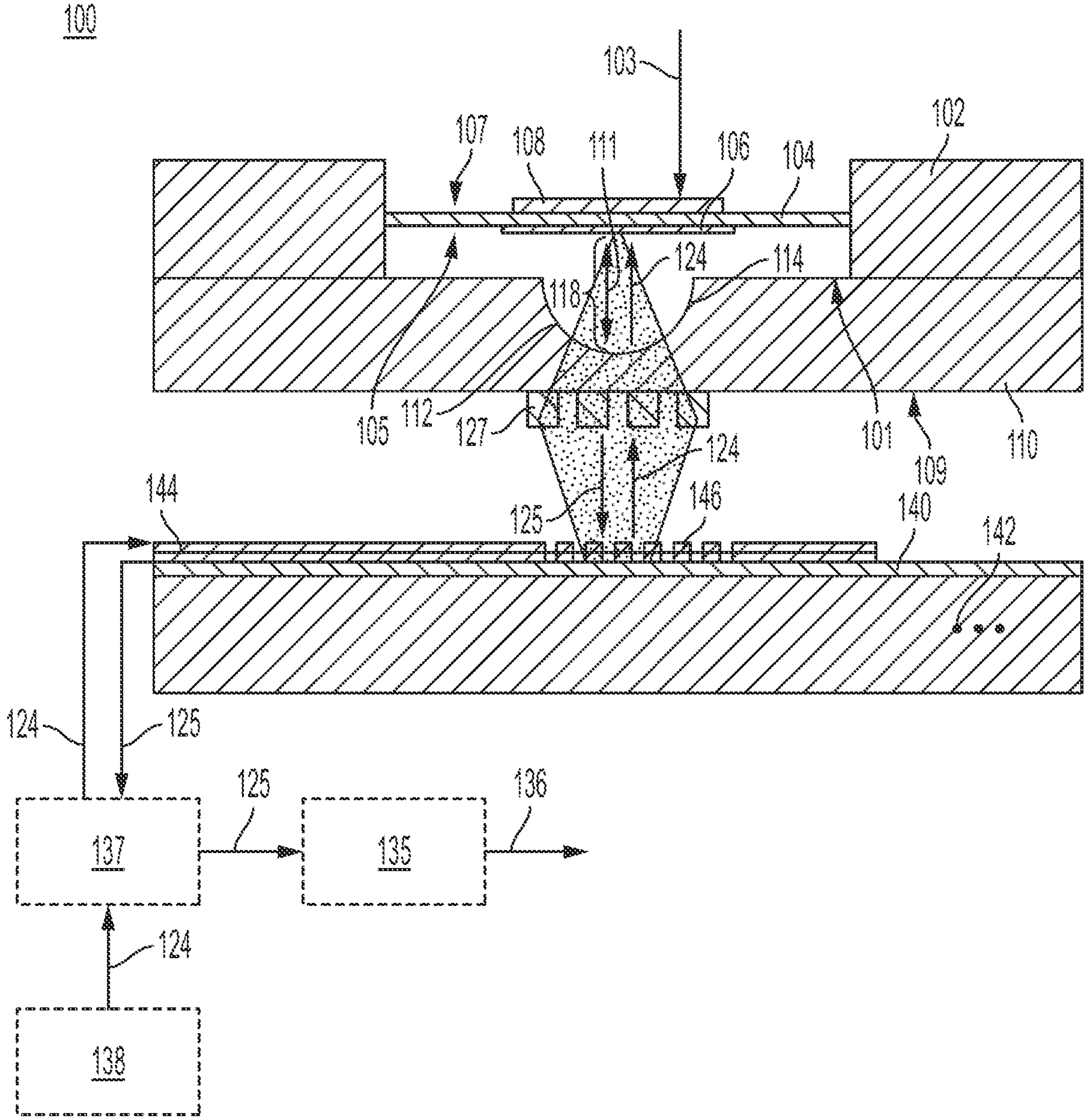

100
103
107
108
111
106
104
102
124
114
118
112
105
127
101
109
110
124
144
125
146
140
142
124
125
125
136
137
135
124
138

FIG. 4

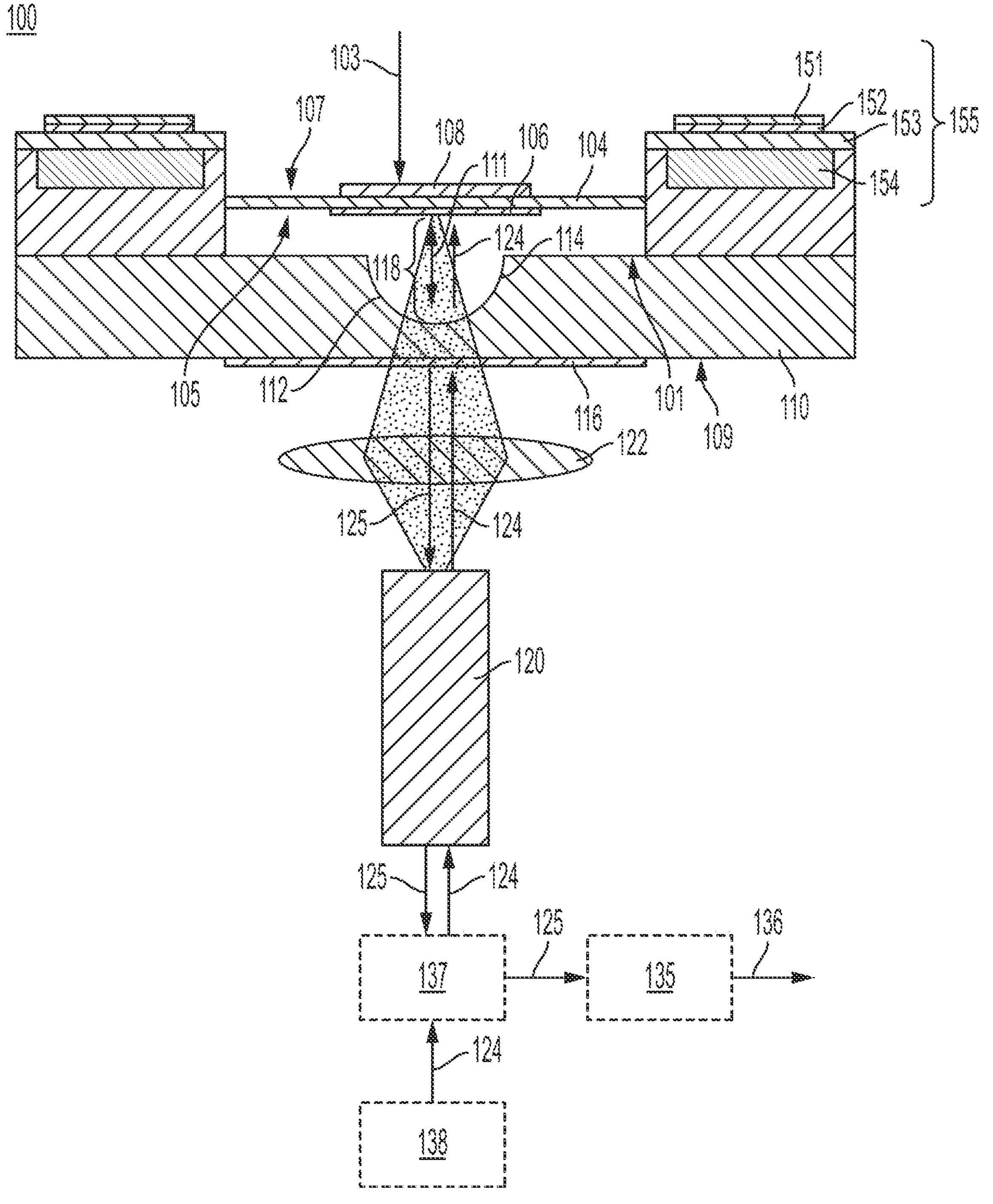

100
103
107
108
111
106
104
151
152
153
155
154
118
124
114
105
112
116
101
109
110
122
125
124
120
125
124
125
136
137
135
124
138

FIG. 5

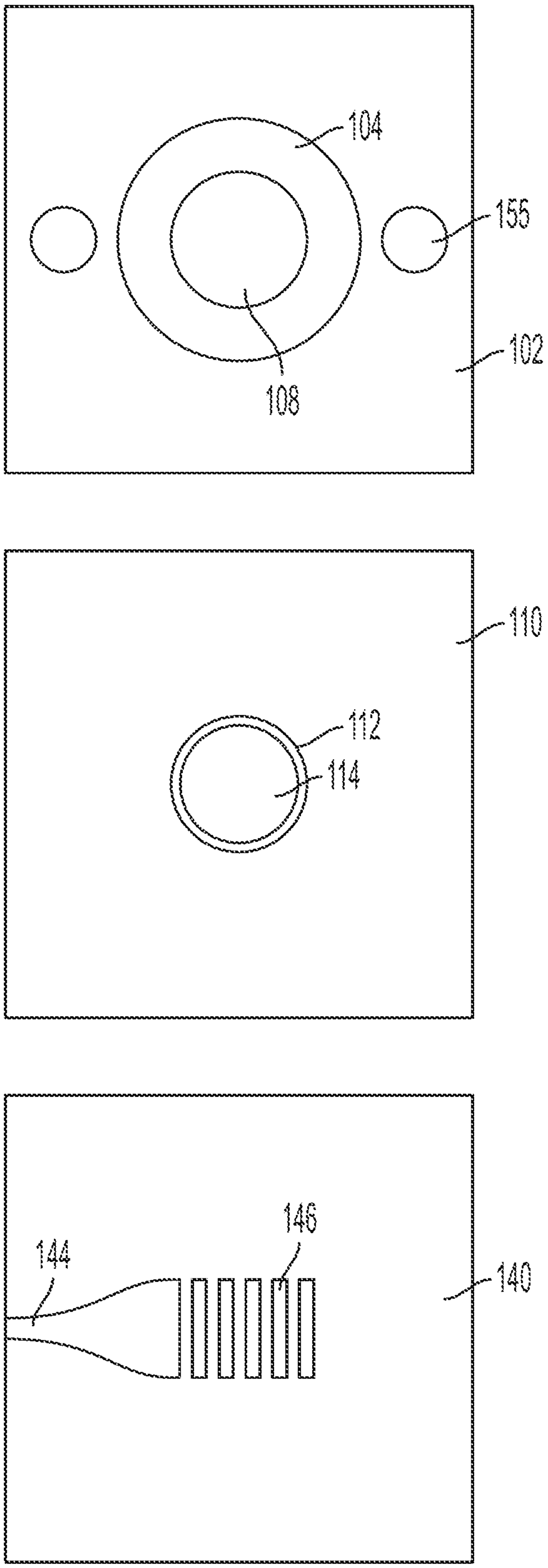


FIG. 6

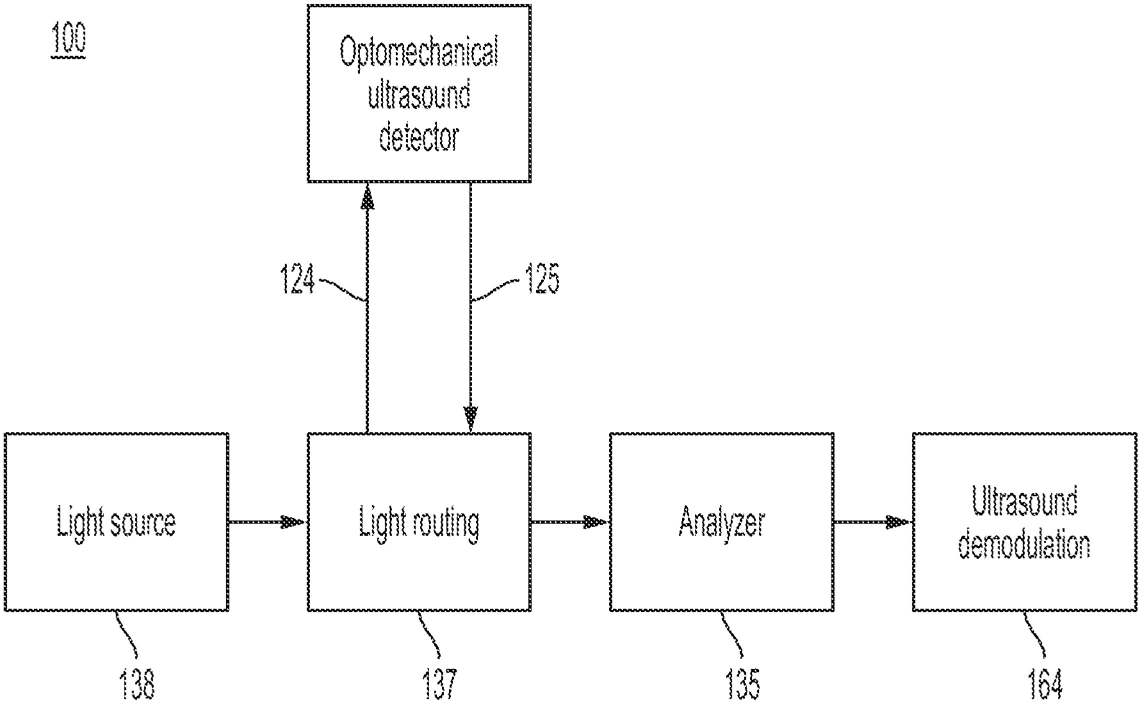

100
Optomechanical ultrasound detector
124
125
Light source
Light routing
Analyzer
Ultrasound demodulation
138
137
135
164

FIG. 7

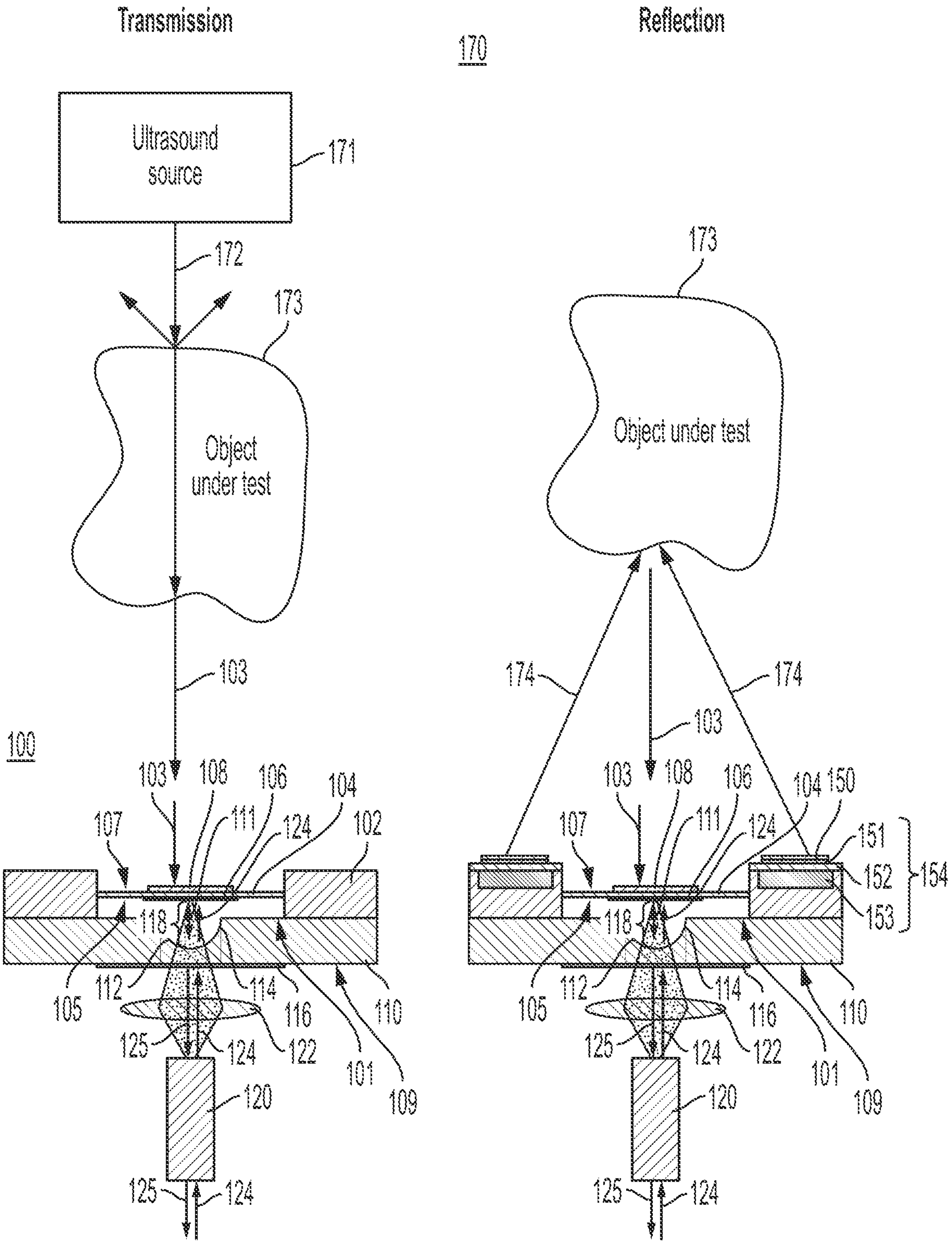

Transmission
Reflection
170
Ultrasound source
171
172
173
Object under test
103
100
103
108
106
104
107
111
124
102
118
105
112
114
116
110
125
124
122
101
109
120
125
124
173
Object under test
174
174
103
103
108
106
104
150
107
111
124
151
152
154
153
118
105
112
114
116
110
125
124
122
101
109
120
125
124

FIG. 8

OPTOMECHANICAL ULTRASOUND DETECTOR AND PERFORMING ULTRASOUND IMAGING

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application Ser. No. 63/216,079 (filed Jun. 29, 2021), which is herein incorporated by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

[0002] This invention was made with United States Government support from the National Institute of Standards and Technology (NIST), an agency of the United States Department of Commerce. The Government has certain rights in this invention.

BRIEF DESCRIPTION

[0003] Disclosed is an optomechanical ultrasound detector for performing ultrasound imaging, the optomechanical ultrasound detector comprising: a micromirror substrate; a mechanical resonator disposed on the micromirror substrate, in optical communication with the micromirror substrate, spaced apart from the micromirror substrate at a cavity length L_c, and that: receives ultrasound waves; oscillates at a resonator frequency f_r in response to receipt of the ultrasound waves; changes the cavity length L_c based on oscillation of the mechanical resonator at resonator frequency f_r; receives initial laser light from the micromirror substrate; and produces intra-cavity light from the initial laser light; and an optical microcavity optically interposed between the micromirror substrate and the mechanical resonator and comprising the cavity length L_c with cavity resonance frequency f_c formed by optically opposing surfaces of the mechanical resonator and the micromirror substrate and that: when the intra-cavity light is resonant with the cavity resonance frequency f_c, repeatedly communicates the intra-cavity light between the micromirror substrate and the mechanical resonator across the cavity length L_c; and when the intra-cavity light is non-resonant with the cavity resonance frequency f_c, communicates the intra-cavity light from the mechanical resonator to the micromirror substrate, such that the micromirror substrate produces cavity output light from the intra-cavity light, wherein the cavity output light optically encodes information about the ultrasound waves received by the mechanical resonator.

[0004] A process for performing ultrasound imaging with a optomechanical ultrasound detector, the process comprising: receiving ultrasound waves by a mechanical resonator of a optomechanical ultrasound detector, the optomechanical ultrasound detector comprising: a micromirror substrate; a mechanical resonator disposed on the micromirror substrate, in optical communication with the micromirror substrate, spaced apart from the micromirror substrate at a cavity length L_c; and an optical microcavity optically interposed between the micromirror substrate and the mechanical resonator and comprising the cavity length L_c with cavity resonance frequency f_c formed by optically opposing surfaces of the mechanical resonator and the micromirror substrate; oscillating the mechanical resonator at a resonator frequency f_r in response to receiving the ultrasound waves; changing the cavity length L_c of the optical microcavity based on oscillation of the mechanical resonator at resonator frequency f_r; communicating initial laser light from the micromirror substrate to the mechanical resonator; receiving, by the mechanical resonator, initial laser light from the micromirror substrate; producing, by the mechanical resonator, intra-cavity light from the initial laser light; optically encoding, by the mechanical resonator, in the cavity output light information about the ultrasound waves received by the mechanical resonator; repeatedly communicating the intra-cavity light between the micromirror substrate and the mechanical resonator across the cavity length L_c when the intra-cavity light is resonant with the cavity resonance frequency f_c; and communicating the intra-cavity light from the mechanical resonator to the micromirror substrate; and producing, by the micromirror substrate, cavity output light from the intra-cavity light to perform ultrasound imaging.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] The following description cannot be considered limiting in any way. Various objectives, features, and advantages of the disclosed subject matter can be more fully appreciated with reference to the following detailed description of the disclosed subject matter when considered in connection with the following drawings, in which like reference numerals identify like elements.

[0006] FIG. **1** shows an optomechanical ultrasound detector, according to some embodiments.

[0007] FIG. **2** shows an optomechanical ultrasound detector, according to some embodiments.

[0008] FIG. **3** shows an optomechanical ultrasound detector, according to some embodiments.

[0009] FIG. **4** shows an optomechanical ultrasound detector, according to some embodiments.

[0010] FIG. **5** shows an optomechanical ultrasound detector, according to some embodiments.

[0011] FIG. **6** shows plan views for a resonator substrate, micromirror substrate, and nanophotonic waveguide on a dielectric layer, according to some embodiments.

[0012] FIG. **7** shows an optomechanical ultrasound detector, according to some embodiments.

[0013] FIG. **8** shows an optomechanical ultrasound detector for transmission mode ultrasound detection and reflection mode ultrasound detection, according to some embodiments.

DETAILED DESCRIPTION

[0014] A detailed description of one or more embodiments is presented herein by way of exemplification and not limitation.

[0015] Conventional ultrasound transducers for medical imaging and structural diagnostics have limited resolution due to stiffness and low sensitivity of piezoelectric elements in such conventional ultrasound transducers. As a result, detecting small changes in material properties and imaging through highly reflective materials has been challenging, if not impossible, with conventional technology. Accordingly, certain conventional technologies have limited use for ultrasound imaging. The optomechanical ultrasound detector **100** described herein overcome these limitations.

[0016] It has been discovered that a optomechanical ultrasound detector **100** described herein ultra-sensitively and optomechanically detects ultrasound waves for ultrasound imaging. Advantageously, the sensitivity of optomechanical ultrasound detector **100** can be at least two orders of magnitude better than conventional technology and sufficient for novel medical imaging modalities, including ultrasound whole brain imaging. Optomechanical ultrasound detector **100** can include a Fabry-Perot optical cavity with a mechanical resonator so that when the mechanical resonator moves under the influence of ultrasound, ultra-sensitive readout of the motion is achieved using the optical cavity and laser light. In addition to sensitivity, the optomechanical ultrasound detector **100** provides greater safety during imaging than conventional devices due to lower ultrasound power that can be used while yielding higher resolution imaging. Performing ultrasound imaging with optomechanical ultrasound detector **100** can be applied for acoustic detection as well as photoacoustic measurements.

[0017] Optomechanical ultrasound detector **100** performs ultrasound imaging. In an embodiment, with reference to FIG. **1**, FIG. **2**, FIG. **3**, FIG. **4**, FIG. **5**, FIG. **6**, FIG. **7**, and FIG. **8**, optomechanical ultrasound detector includes: a micromirror substrate **110**; a mechanical resonator **104** disposed on the micromirror substrate **110**, in optical communication with the micromirror substrate **110**, spaced apart from the micromirror substrate **110** at a cavity length Lc, and that: receives ultrasound waves **103**; oscillates at a resonator frequency fr in response to receipt of the ultrasound waves **103**; changes the cavity length Lc based on oscillation of the mechanical resonator **104** at resonator frequency fr; receives initial laser light **124** from the micromirror substrate **110**; and produces intra-cavity light **111** from the initial laser light **124**; and an optical microcavity **118** optically interposed between the micromirror substrate **110** and the mechanical resonator **104** and including the cavity length Lc with cavity resonance frequency fc formed by optically opposing surfaces of the mechanical resonator **104** and the micromirror substrate **110** and that: when the intra-cavity light **111** is resonant with the cavity resonance frequency fc, repeatedly communicates the intra-cavity light **111** between the micromirror substrate **110** and the mechanical resonator **104** across the cavity length Lc; and when the intra-cavity light **111** is non-resonant with the cavity resonance frequency fc, communicates the intra-cavity light **111** from the mechanical resonator **104** to the micromirror substrate **110**, such that the micromirror substrate **110** produces cavity output light **125** from the intra-cavity light **111**, wherein the cavity output light **125** optically encodes information about the ultrasound waves **103** received by the mechanical resonator **104**.

[0018] In an embodiment, optomechanical ultrasound detector **100** includes resonator substrate **102** disposed on the micromirror substrate **110** and on which the mechanical resonator **104** is disposed.

[0019] In an embodiment, optomechanical ultrasound detector **100** includes anti-reflective member **108** disposed on an ultrasound surface **107** of the mechanical resonator **104** and that receives the ultrasound waves **103**.

[0020] In an embodiment, optomechanical ultrasound detector **100** includes resonator optical reflector **106** disposed on a reflector surface **105** of the mechanical resonator **104** and that receives the initial laser light **124** from the micromirror substrate **110** and reflects the initial laser light **124** as the intra-cavity light **111**.

[0021] In an embodiment, optomechanical ultrasound detector **100** includes mirror anti-reflective member **116** disposed on an optical coupling surface **109** of the micromirror substrate **110** and that receives the initial laser light **124**, communicates the initial laser light **124** to the mechanical resonator **104** via the optical microcavity **118**, receives the intra-cavity light **111** from the optical microcavity **118**, and produces the cavity output light **125** from the intra-cavity light **111**.

[0022] In an embodiment, optomechanical ultrasound detector **100** includes concave micromirror **112** disposed on an optical coupling surface **109** of the micromirror substrate **110**, such that the concave micromirror **112** is arranged to be optically concave with respect to the optical microcavity **118**.

[0023] In an embodiment, optomechanical ultrasound detector **100** includes mirror reflective member **114** disposed on a cavity surface **101** of the micromirror substrate **110** and that receives the initial laser light **124** from the micromirror substrate **110** and is an intra-cavity mirror for the optical microcavity **118**, such that the mirror reflective member **114**: reflects the intra-cavity light **111** when the intra-cavity light **111** is resonant with the cavity resonance frequency f_c; and communicates the intra-cavity light **111** to the micromirror substrate **110** when the intra-cavity light **111** is non-resonant with the cavity resonance frequency f_c.

[0024] In an embodiment, optomechanical ultrasound detector **100** includes optical fiber **120** in optical communication with the micromirror substrate **110** and that communicates the initial laser light **124** to the micromirror substrate **110** and receives the cavity output light **125** from the micromirror substrate **110**. In an embodiment, optomechanical ultrasound detector **100** includes coupling lens **122** in optical communication with the micromirror substrate **110** and that receives the initial laser light **124**, communicates the initial laser light **124** to the micromirror substrate **110**, and receives the cavity output light **125** from the micromirror substrate **110**, wherein the micromirror substrate **110** is interposed between coupling lens **122** and the optical microcavity **118**. The coupling lens **122** can be disposed on the micromirror substrate **110**. In an embodiment, mirror anti-reflective member **116** is disposed on the coupling lens **122**, wherein the coupling lens **122** is interposed between the mirror anti-reflective member **116** and the micromirror substrate **110**.

[0025] In an embodiment, optomechanical ultrasound detector **100** includes nanophotonic waveguide **144** in optical communication with the micromirror substrate **110** and that receives the initial laser light **124**, communicates the initial laser light **124** to the micromirror substrate **110**, and receives the cavity output light **125** from the micromirror substrate **110**. The micromirror substrate **110** can be interposed between nanophotonic waveguide **144** and the optical microcavity **118**. In an embodiment, nanophotonic waveguide **144** includes nanophotonic coupling member **146** in optical communication with the micromirror substrate **110** and that receives the initial laser light **124**, communicates the initial laser light **124** to the micromirror substrate **110**, and receives the cavity output light **125** from the micromirror substrate **110**. The micromirror substrate **110** can be interposed between nanophotonic coupling member **146** and the optical microcavity **118**. In an embodiment, optomechanical ultrasound detector **100** includes nanophotonic substrate **142** on which the nanophotonic waveguide **144** is disposed. In an embodiment, optomechanical ultrasound detector **100** includes a dielectric layer **140** disposed on the nanophotonic substrate **142** such that the dielectric layer **140**

is interposed between the nanophotonic substrate **142** and the nanophotonic waveguide **144**.

[0026] In an embodiment, optomechanical ultrasound detector **100** includes meta-optic **127** disposed on the micromirror substrate **110** in optical communication with the micromirror substrate **110** and that receives the initial laser light **124**, communicates the initial laser light **124** to the micromirror substrate **110**, and receives the cavity output light **125** from the micromirror substrate **110**. The micromirror substrate **110** can be interposed between the meta-optic **127** and the optical microcavity **118**.

[0027] When ultrasound waves **103** impinge mechanical resonator **104**, mechanical resonator **104** displaces periodically due to the pressure wave generated by ultrasound waves **103**. The optical microcavity **118** transduces motion of ultrasound waves **103**. Various optical readout configurations and processes can be included to determine how cavity length L_c of optical microcavity **118** changes as a function of time and to determining the motion of mechanical resonator **104**. The motion of mechanical resonator **104** detects presence of ultrasound waves **103**, e.g., as ultrasound reflections during imaging. Such reflections are used to construct images of a sample under inspection. Due to a high displacement sensitivity provided by this optical microcavity readout, the optomechanical ultrasound detector **100** has higher sensitivity to ultrasound waves **103** than conventional detectors.

[0028] The optomechanical ultrasound detector **100** includes optical fiber **120** and coupling lens **122** to send initial laser light **124** into optical microcavity **118** and to collect cavity output light **125** reflected from mechanical resonator **104** and output from optical microcavity **118**. The initial laser light **124** can be communicated into optical microcavity **118** in various ways and configurations, such as with integrated lens **122**, e.g., as shown in FIG. **2**. The optomechanical ultrasound detector **100** can include communication of initial laser light **124** via nanophotonic structures such as nanophotonic waveguide **144**. The optomechanical ultrasound detector **100** with integrated lens **122** can include optical fiber **120**, and initial laser light **124** can be coupled into optical microcavity **118** by coupling lens **122** disposed on micromirror substrate **110**, which can provide a reduction in size of optomechanical ultrasound detector **100**. The optomechanical ultrasound detector **100** with nanophotonic light delivery **144** further can reduce the size of optomechanical ultrasound detector **100** by replacing the optical fiber **120** with a nanophotonic substrate **142** and nanophotonic coupling member **146**. The nanophotonic substrate **142** couples light from a nanophotonic waveguide **144**, through a nanophotonic coupling member **146**, passing initial laser light **124** through integrated lens **122**, and into optical microcavity **118** so that optomechanical ultrasound detector **100** can be formed by stacked substrates that can be aligned and bonded in an absence of laborious manual assembly.

[0029] It is contemplated that optomechanical ultrasound detector **100** can be a single detector or arranged into one-dimensional, two-dimensional, and the like arrays for wide-field ultrasound imaging.

[0030] Optomechanical ultrasound detector **100** can be made of various elements and components that are assembled, formed, or fabricated in a number of ways, e.g., microfabrication, wherein mechanical resonator **104** is a mechanical resonator that is suspended by resonator substrate **102** proximate to micromirror substrate **110**. In this manner, resonator substrate **102** supports mechanical resonator **104**, which results in a cavity length L_c providing a separation between resonance modes of optical microcavity **118**. On a separate microfabricated chip, concave micromirror **112** can be formed in micromirror substrate **110**. When the chips containing mechanical resonator **104** and concave micromirror **112** are assembled together, they form optical microcavity **118**, wherein opposing surfaces of mechanical resonator **104** and concave micromirror **112** have high reflectivity coatings disposed thereon respectively as resonator optical reflector **106** and mirror reflective member **114**. Motion of the mechanical resonator **104** is measured by using analyzer **135** to detect changes in optical resonances of optical microcavity **118** through communication of intra-cavity light **111** and cavity output light **125** produced from ultrasound waves **103** that cause oscillation of mechanical resonator **104** relative to micromirror substrate **110**. That is, ultrasound waves **103** are transduced into intra-cavity light **111** by mechanical resonator **104** that is coupled into optical microcavity **118** as intra-cavity light **111** and repeatedly reflected between mechanical resonator **104** and micromirror substrate **110** at cavity resonance frequency f_c before being communicated out of optical microcavity **118** as cavity output light **125**, wherein cavity output light **125** is received by analyzer **135**. Micromirror substrate **110** provides a stable cavity design that can be, e.g., a hemispherical cavity, and high reflectivity coatings are included to provide high optical finesse that results in high displacement sensitivity of mechanical resonator **104** relative to concave micromirror **112**. Coatings and materials used for mechanical resonator **104** and concave micromirror **112** can be selected for operation with laser wavelengths for micromirror substrate **110** and mirror reflective member **114** that can include visible light from 400 nm to 700 nm, near infrared light from 700 nm to 1000 nm, or short-wave infrared from 1000 nm to 3000 nm. Operation with a laser wavelength near 1550 nm can provide integration with a large number of fiber optic components designed for telecommunications, making optomechanical ultrasound detector **100** scalable and compatible with off-the-shelf optical characterization tools.

[0031] Elements of optomechanical ultrasound detector **100** can be various sizes. It is contemplated that materials for micromirror substrate **110** and other optical elements can be selected based on a resonance frequency desired for optical microcavity **118**. The cavity length L of optical microcavity **118**, e.g., can be from 1 micrometer (μm) to 50 millimeters (mm), specifically from 10 micrometer (μm) to 5 millimeters (mm), and more specifically from 100 μm to 10 mm, although other suitable cavity lengths can be included.

[0032] Elements of micromirror substrate **110** can be made of a material that is physically or chemically resilient in an environment in which micromirror substrate **110** is disposed. Exemplary materials include a metal, ceramic, thermoplastic, glass, semiconductor, and the like. The elements of micromirror substrate **110** can be made of the same or different material and can be monolithic in a single physical body or can be separate members that are phsycially joined. Transmission of a selected wavelength of light, e.g., for micromirror substrate **110**, can be provided by the material used for such optical elements. For example, tranmission of visible light by micromirror substrate **110** or concave micromirror **112** can be provided by fused silica.

[0033] In an embodiment, mechanical resonator **104** is a continuous mechanical structure connected to resonator substrate **102** on all sides and with a resonator frequency f_r, e.g., from 0.5 MHz to 100 MHz to coincide with the frequencies used in ultrasound imaging, or another frequency that can be selected for a chosen application. The shape of the mechanical resonator **104** in the plane of resonator substrate **102** can be arbitrary, wherein exemplary shapes include circular or polygonal (e.g., square, hexagonal, and the like). A planar dimension can be, e.g., from 50 μm to 2 mm. The resonator optical reflector **106** and anti-reflective member **108** can include a Bragg grating that can include, e.g., layered dielectric materials, a two-dimensional photonic crystal that can be disposed on or into mechanical resonator **104**. The resonator optical reflector **106** can have reflectivity from 20% to 99.999% that can depend on its design and fabrication. The anti-reflective member **108** can have a stiffness perpendicular to resonator substrate **102** due to bending stiffness or tension in the material. While not being limited to such, exemplary materials for mechanical resonator **104** include silicon, silicon nitride, silicon dioxide, silicon carbide, fused silica, and the like.

[0034] The concave micromirror **112** can be semispherical in an area where initial laser light **124** or cavity output light **125** propagate through the mirror, The mirror reflective member **114** and mirror anti-reflective member **116** on concave micromirror **112** independently can be a Bragg grating that includes, e.g., layered dielectric materials. The mirror reflective member **114** can have a reflectivity from 20% to 99.999%, e.g., based on its design and fabrication. While not limited thereto, exemplary materials for concave micromirror **112** include silicon, silicon nitride, silicon dioxide, silicon carbide, fused silica, and the like. The radius of concave micromirror **112** and the distance between concave micromirror **112** and mechanical resonator **104** is selected so that optical microcavity **118** is an optically stable microcavity.

[0035] Laser light **124** can have a wavelength ranging from 400 nm to 1700 nm depending on the materials selected for the detector, e.g., analyzer **135**. A light source **138** can produce the initial laser light **124** at a fixed or tunable frequency. An optical splitter **137** can communicate initial laser light **124** from light source **138** to micromirror substrate **110** and communicate cavity output light **125** from micromirror substrate **110** to analyzer **135**. The optical splitter **137** can include suitable optical and electrical components for this operation such as a mirror, beam splitter, motor, mixer, and the like.

[0036] The coupling lens **122** has a focal length that provides efficient mode coupling of initial laser light **124** into optical microcavity **118** and can be made from and include various materials. Exemplary materials for coupling lens **122** include including silicon, silicon nitride, silicon dioxide, silicon carbide, fused silica, titanium oxide, aluminum oxide, polymer, and the like. The coupling lens **122** can be interposed between micromirror substrate **110** and light source **138** either spaced apart from micromirror substrate **110** or disposed on micromirror substrate **110**. The coupling lens **122** can have various geometrical shapes and formats such as plano-concave for disposal on micromirror substrate **110** or a meta-optic **127** such as a flat meta-lens, as shown in FIG. **4**. The meta-optic **127** can include, e.g., a periodic nanostructure, nanofabricated Fresnel lens, and the like.

[0037] Nanophotonic substrate **142** can be included in optomechanical ultrasound detector **100**. In some embodiments, nanophotonic substrate **142** is include instead of optical fiber **120** or coupling lens **122**. Nanophotonic waveguide **144** receives initial laser light **124** disposed on nanophotonic substrate **142**. The nanophotonic waveguide **144** confines laser light (**124**, **125**) with low optical attenuation. Dielectric layer **140** constrains light to propagate in nanophotonic waveguide **144** without communication into nanophotonic substrate **142**. The nanophotonic waveguide **144** communicates initial laser light **124** to nanophotonic coupling member **146** and receives cavity output light **125** from nanophotonic coupling member **146**. The nanophotonic coupling member **146** can include a periodic nanostructure that communicates laser light (**124**, **125**) perpendicular to nanophotonic substrate **142** with a selected numerical aperture and beam width. Non-limiting examples of materials for elements disposed on nanophotonic substrate **142** include silicon, silicon nitride, silicon dioxide, silicon carbide, fused silica, titanium oxide, aluminum oxide, polymer, and the like. When flat meta-lens **127** is disposed on micromirror substrate **110** and includes the periodic nanostructure or nanofabricated Fresnel lens, resonator substrate **102**, micromirror substrate **110**, and nanophotonic substrate **142** can be bonded together to form a monolithic and compact detector of ultrasound waves **103**.

[0038] In an embodiment, with reference to FIG. **5**, optomechanical ultrasound detector **100** includes an integrated piezoelectric ultrasound source **155**. The integrated piezoelectric ultrasound source **155** can include metal layer **151**, piezoelectric material **152**, vibrating membrane **153**, and optional air cavity **154**. When an electrical pulse is applied to metal layer **151**, piezoelectric material **152** expands and deforms vibrating membrane **153**. An electrical pulse with a selected frequency and power produces an ultrasound wave that propagates from optomechanical ultrasound detector **100** until incident at an object external to optomechanical ultrasound detector **100**. Some energy of this ultrasound wave reflects from the object and is detected by optomechanical ultrasound detector **100**.

[0039] It should be appreciated that optomechanical ultrasound detector **100** includes optical microcavity **118** that is an optical cavity that can include a hemispherical micromirror formed in a micromirror substrate **110** that can be bonded to resonator substrate **102** having disposed thereon mechanical resonator **104** with resonator optical reflector **106** that can be a flat mirror. Beneficially, optomechanical ultrasound detector **100** can fill a volume less than a cubic millimeter. Ultrasound waves **103** incident on mechanical resonator **104** cause oscillation of mechanical resonator **104**, which shifts the cavity resonance frequency f_c of optical microcavity **118**. The cavity resonance frequency f_c can be measured continuously to detect the oscillation of mechanical resonator **104** and amplitude and phase of ultrasound waves **103**.

[0040] The concave micromirror and mechanical resonator chips can be microfabricated in substrates that can include silicon, glass, or other dielectrics or semiconductors, The concave micromirror and mechanical resonator independently can have high reflectivity surfaces for high finesse or low optical loss in optical microcavity **118**. This increases the sensitivity of optomechanical ultrasound detector **100**. The high reflectivity surfaces could be dielectric Bragg mirror coatings, photonic crystals, or optical meta-surfaces.

The backside of the concave mirror chip can have an antireflection coating to minimize parasitic cavities between the various surfaces in the bonded chip stack.

[0041] The mechanical resonator **104** can be a plate (e.g., material having bending stiffness) or a membrane (e,g., a material under tension with minimal bending stiffness). The planar geometry of the plate or membrane can be arbitrary, e.g., circular or square. The thickness and planar dimensions of the mechanical resonator **104** can be selected for a selected resonance frequency or compliance based on an application. Medical ultrasound imaging can occur from 1 MHz to 20 MHz, and imaging resolution limit set by the ultrasound frequency and acoustic velocity of the human body can be from 0.1 mm and 1 mm. The mechanical resonator **104** provides imaging in view of these characteristics. When operating at 20 MHz with a circular resonator, the diameter of mechanical resonator **104** can be, e,g., 0.1 mm.

[0042] Light (e.g., **124**, **125**) is coupled into and out of the optical cavity **118** with optical fiber **120** and lens **122**. The optical cavity **118** sensitively optically transduces displacement of the mechanical resonator **104**. Transduction of the displacement with analyzer **135** and a laser **137** can include sideband laser locking, Pound-Drever-Hall laser locking, and the like.

[0043] Optomechanical ultrasound detector **100** can be made in various ways. It should be appreciated that optomechanical ultrasound detector **100** includes a number of optical, electrical, or mechanical components, wherein such components can be interconnected and placed in communication (e.g., optical communication, electrical communication, mechanical communication, and the like) by physical, chemical, optical, or free-space interconnects. The components can be disposed on mounts that can be disposed on a bulkhead for alignment or physical compartmentalization. As a result, optomechanical ultrasound detector **100** can be disposed in a terrestrial environment or space environment. Elements of optomechanical ultrasound detector **100** can be formed from silicon, silicon nitride, and the like although other suitable materials, such ceramic, glass, or metal can be used. According to an embodiment, the elements of optomechanical ultrasound detector **100** are formed using microfabrication processing techniques. It should be appreciated that optomechanical ultrasound detector **100** can be made by additive or subtractive manufacturing. In an embodiment, elements of optomechanical ultrasound detector **100** are selectively etched to remove various different materials using different etchants and photolithographic masks and procedures. The various layers thus formed can be subjected to joining by bonding to form optomechanical ultrasound detector **100**.

[0044] According to an embodiment, a process for making mechanical resonator **104** includes: providing a base material, e.g., a silicon-on-insulator wafer, wherein the wafer can include various layers, e.g., a stack of materials such as a silicon handle wafer (e.g., thickness from 300 μm to 900 μm), a silicon dioxide layer (e.g., thickness from 500 nm to 2 μm), and a silicon device layer (e.g., thickness from 200 nm to 50 μm), such that the base member is subjected to modification for forming mechanical resonator **104**; subjecting device layer of the base material to photolithography and to deep reactive ion etching to etch down to the silicon dioxide layer and forming independent mechanical resonators; subjecting the handle wafer to photolithography and deep reactive ion etching to etch down to the silicon oxide layer and forming a planar shape of mechanical resonator **104**; separating the mechanical resonators into individual chips, wherein separating can involve using a dicing saw; and forming resonator optical reflector **106**, mirror anti-reflective member **116**, other reflective elements, or other anti-reflective elements with shadow masking and ion beam sputtering for Bragg grating tantalum-pentoxide/silicon dioxide coatings.

[0045] According to an embodiment, a process for making concave micromirror **112** includes: providing a silicon wafer with thickness ranging from 300 μm to 900 μm; using photolithography and deep reactive ion etching to etch a trench in the top surface of the silicon wafer to form a trench that is square and between 0.5 mm and 5 mm wide; after cleaning the wafer, depositing silicon nitride on both sides of the wafer using chemical vapor deposition with a thickness between 200 nm and 1000 nm; using photolithography and reactive ion etching to etch a circular aperture through the silicon nitride layer located at the center of the square trench; using hydrofluoric acid, nitric acid, and acetic acid at room temperature to etch the silicon exposed by the circular aperture, resulting in a semispherical concave micromirror; using heated phosphoric acid to remove the silicon nitride layer and then clean the wafer; using a dicing saw to separate the concave micromirrors into chips; and using shadow masking with ion beam sputtering for Bragg grating tantalum-pentoxide/silicon dioxide coatings to apply the reflective element and anti-reflective element.

[0046] According to an embodiment, a process for making optomechanical ultrasound detector **100** includes: bonding a silicon chip including a concave micromirror to a chip containing a mechanical resonator using silicon fusion bonding; aligning the bonded chip stack to an optical fiber and coupling lens that are located in a metal package with a flat surface for holding the chip stack; and using a low-stress adhesive to bond the chip stack to the metal package to make optomechanical ultrasound detector **100**.

[0047] Optomechanical ultrasound detector has numerous advantageous and unexpected benefits and uses. In an embodiment, a process for performing ultrasound imaging with optomechanical ultrasound detector **100** includes: receiving ultrasound waves **103** by a mechanical resonator **104** of a optomechanical ultrasound detector **100**, oscillating the mechanical resonator **104** at a resonator frequency fr in response to receiving the ultrasound waves **103**; changing the cavity length Lc of the optical microcavity **118** based on oscillation of the mechanical resonator **104** at resonator frequency fr; communicating initial laser light **124** from the micromirror substrate **110** to the mechanical resonator **104**; receiving, by the mechanical resonator **104**, initial laser light **124** from the micromirror substrate **110**; producing, by the mechanical resonator **104**, intra-cavity light **111** from the initial laser light **124**; optically encoding, by the mechanical resonator **104**, in the cavity output light **125** information about the ultrasound waves **103** received by the mechanical resonator **104**; repeatedly communicating the intra-cavity light **111** between the micromirror substrate **110** and the mechanical resonator **104** across the cavity length Lc when the intra-cavity light **111** is resonant with the cavity resonance frequency fc; communicating the intra-cavity light **111** from the mechanical resonator **104** to the micromirror substrate **110**; and producing, by the micromirror substrate

110, cavity output light **125** from the intra-cavity light **111** to perform ultrasound imaging.

[0048] In an embodiment, the process for performing ultrasound imaging includes communicating the cavity output light **125** from the micromirror substrate **110** to an analyzer **135**.

[0049] In an embodiment, the process for performing ultrasound imaging includes, performing by the analyzer **135**: receiving the cavity output light **125**; analyzing the cavity output light **125**; and determining the information about the ultrasound waves **103** from analyzing the cavity output light **125**.

[0050] In an embodiment, a process for performing ultrasound imaging includes receiving initial laser light **124** by optomechanical ultrasound detector **100**, wherein the wavelength of laser light **124** is set so that part of initial laser light **124** is received in optical microcavity **118**, and multiple wavelengths can be used simultaneously. The initial laser light **124** entering optical microcavity **118** circulates intra-cavity light **111** and initial laser light **124** in optical microcavity **118**, reflecting from mirror reflector member (**106**, **114**). Laser light is continuously coupled into and re-emitted by the cavity **118**. As the mechanical resonator **104** oscillates in response to receipt of ultrasound waves **103**, mechanical resonator **104** changes cavity length L_c and the intensity or frequency in a spectrum of intra-cavity light **111** and initial laser light **124** in optical microcavity **118**. Some of intra-cavity light **111** exits optical microcavity **118** as cavity output light **125** through the concave micromirror **112** and propagates toward the light routing element **162** (e.g., optical splitter **137**), as shown in FIG. **7**. Intensity or frequency of cavity output light **125** communicated from optical microcavity **118** is measured to determine motion of the mechanical resonator **104**. The intensity or frequency of initial laser light **124** can be changed to enhance detection of cavity output light **125**, including simultaneous use of multiple wavelengths.

[0051] In an embodiment, with reference to FIG. **7**, optomechanical ultrasound detector **100** can include laser source **161** that introduces light into the detection system. The laser source can produce light with variable frequency or at multiple wavelengths. Light routing element **162** sends laser light **124** to the ultrasound detector so that light re-emitted by the detector **125** can be analyzed. An analyzer **163** converts the light re-emitted by the detector into an electronic signal representing the representing the instantaneous ultrasound amplitude as measured by the motion of the detector element under the influence of the ultrasound waves. An ultrasound demodulation element **164** demodulates and analyzes the electronic signal from the analyzer to yield ultrasound measurements and images.

[0052] Measurement with the optomechanical ultrasound detector can be configured in various ways. In an embodiment, an ultrasound signal (an acoustic wave or pulse at ultrasonic frequencies) is produced by a source. The source may be separate from the detector **171** or integrated with it **155**. In an embodiment, the signal interacts with an object under test that scatters it (including absorption, transmission, and reflection, possibly accompanied by changes in amplitude or frequency). In an embodiment, some of the scattered signal **103** impinges on the detector where it causes a mechanical element **104** to vibrate. In an embodiment, the vibration of mechanical resonator **104** changes the optical spectrum of the detector by changing the length of the cavity **118**. Accordingly, optomechanical ultrasound detector **100** measures the change in the optical spectrum to track the motion of the mechanical element **104** and measure the ultrasound waves **103**.

[0053] Optomechanical ultrasound detector **100** and processes disclosed herein have numerous beneficial uses. Advantageously, optomechanical ultrasound detector **100** is more sensitive than conventional detectors. For example, optomechanical ultrasound detector **100** can be approximately two orders of magnitude more sensitive than piezoelectric detectors and can detect very weak signals that are transmitted through a cranium for neuroimaging, which can be used in treatment of head trauma, e.g., in emergency medicine.

[0054] While one or more embodiments have been shown and described, modifications and substitutions may be made thereto without departing from the spirit and scope of the invention. Accordingly, it is to be understood that the present invention has been described by way of illustrations and not limitation. Embodiments herein can be used independently or can be combined.

[0055] All ranges disclosed herein are inclusive of the endpoints, and the endpoints are independently combinable with each other. The ranges are continuous and thus contain every value and subset thereof in the range. Unless otherwise stated or contextually inapplicable, all percentages, when expressing a quantity, are weight percentages. The suffix (s) as used herein is intended to include both the singular and the plural of the term that it modifies, thereby including at least one of that term (e.g., the colorant(s) includes at least one colorants). Option, optional, or optionally means that the subsequently described event or circumstance can or cannot occur, and that the description includes instances where the event occurs and instances where it does not. As used herein, combination is inclusive of blends, mixtures, alloys, reaction products, collection of elements, and the like.

[0056] As used herein, a combination thereof refers to a combination comprising at least one of the named constituents, components, compounds, or elements, optionally together with one or more of the same class of constituents, components, compounds, or elements.

[0057] All references are incorporated herein by reference.

[0058] The use of the terms "a," "an," and "the" and similar referents in the context of describing the invention (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. It can further be noted that the terms first, second, primary, secondary, and the like herein do not denote any order, quantity, or importance, but rather are used to distinguish one element from another. It will also be understood that, although the terms first, second, etc. are, in some instances, used herein to describe various elements, these elements should not be limited by these terms. For example, a first current could be termed a second current, and, similarly, a second current could be termed a first current, without departing from the scope of the various described embodiments. The first current and the second current are both currents, but they are not the same condition unless explicitly stated as such.

[0059] The modifier about used in connection with a quantity is inclusive of the stated value and has the meaning dictated by the context (e.g., it includes the degree of error associated with measurement of the particular quantity). The conjunction or is used to link objects of a list or alternatives and is not disjunctive; rather the elements can be used separately or can be combined together under appropriate circumstances.

What is claimed is:

1. An optomechanical ultrasound detector for performing ultrasound imaging, the optomechanical ultrasound detector comprising:

a micromirror substrate;

a mechanical resonator disposed on the micromirror substrate, in optical communication with the micromirror substrate, spaced apart from the micromirror substrate at a cavity length L_c, and that:

receives ultrasound waves;

oscillates at a resonator frequency f_r in response to receipt of the ultrasound waves;

changes the cavity length L_c based on oscillation of the mechanical resonator at resonator frequency f_r;

receives initial laser light from the micromirror substrate; and

produces intra-cavity light from the initial laser light; and

an optical microcavity optically interposed between the micromirror substrate and the mechanical resonator and comprising the cavity length L_c with cavity resonance frequency f_c formed by optically opposing surfaces of the mechanical resonator and the micromirror substrate and that:

when the intra-cavity light is resonant with the cavity resonance frequency f_c, repeatedly communicates the intra-cavity light between the micromirror substrate and the mechanical resonator across the cavity length L_c; and

when the intra-cavity light is non-resonant with the cavity resonance frequency f_c, communicates the intra-cavity light from the mechanical resonator to the micromirror substrate, such that the micromirror substrate produces cavity output light from the intra-cavity light,

wherein the cavity output light optically encodes information about the ultrasound waves received by the mechanical resonator.

2. The optomechanical ultrasound detector of claim **1**, further comprising a resonator substrate disposed on the micromirror substrate and on which the mechanical resonator is disposed.

3. The optomechanical ultrasound detector of claim **1**, further comprising an anti-reflective member disposed on an ultrasound surface of the mechanical resonator and that receives the ultrasound waves.

4. The optomechanical ultrasound detector of claim **1**, further comprising a resonator optical reflector disposed on a reflector surface of the mechanical resonator and that receives the initial laser light from the micromirror substrate and reflects the initial laser light as the intra-cavity light.

5. The optomechanical ultrasound detector of claim **1**, further comprising a mirror anti-reflective member disposed on an optical coupling surface of the micromirror substrate and that receives the initial laser light, communicates the initial laser light to the mechanical resonator via the optical microcavity, receives the intra-cavity light from the optical microcavity, and produces the cavity output light from the intra-cavity light.

6. The optomechanical ultrasound detector of claim **1**, further comprising a concave micromirror disposed on an optical coupling surface of the micromirror substrate, such that the concave micromirror is arranged to be optically concave with respect to the optical microcavity.

7. The optomechanical ultrasound detector of claim **6**, further comprising a mirror reflective member disposed on a cavity surface of the micromirror substrate and that receives the initial laser light from the micromirror substrate and is an intra-cavity mirror for the optical microcavity, such that the mirror reflective member:

reflects the intra-cavity light when the intra-cavity light is resonant with the cavity resonance frequency f_c; and

communicates the intra-cavity light to the micromirror substrate when the intra-cavity light is non-resonant with the cavity resonance frequency f_c.

8. The optomechanical ultrasound detector of claim **1**, further comprising an optical fiber in optical communication with the micromirror substrate and that communicates the initial laser fight to the micromirror substrate and receives the cavity output light from the micromirror substrate.

9. The optomechanical ultrasound detector of claim **1**, further comprising a coupling lens in optical communication with the micromirror substrate and that receives the initial laser light, communicates the initial laser light to the micromirror substrate, and receives the cavity output light from the micromirror substrate,

wherein the micromirror substrate is interposed between coupling lens and the optical microcavity.

10. The optomechanical ultrasound detector of claim **9**, wherein the coupling lens is disposed on the micromirror substrate.

11. The optomechanical ultrasound detector of claim **10**, further comprising an mirror anti-reflective member disposed on the coupling lens, wherein the coupling lens is interposed between the mirror anti-reflective member disposed and the micromirror substrate.

12. The optomechanical ultrasound detector of claim **1**, further comprising a nanophotonic waveguide in optical communication with the micromirror substrate and that receives the initial laser light, communicates the initial laser light to the micromirror substrate, and receives the cavity output light from the micromirror substrate,

wherein the micromirror substrate is interposed between nanophotonic waveguide and the optical microcavity.

13. The optomechanical ultrasound detector of claim **12**, wherein the nanophotonic waveguide comprises a nanophotonic coupling member in optical communication with the micromirror substrate and that receives the initial laser light, communicates the initial laser light to the micromirror substrate, and receives the cavity output light from the micromirror substrate,

wherein the micromirror substrate is interposed between nanophotonic coupling member and the optical microcavity.

14. The optomechanical ultrasound detector of claim **13**, further comprising a nanophotonic substrate on which the nanophotonic waveguide is disposed.

15. The optomechanical ultrasound detector of claim **14**, further comprising a dielectric layer disposed on the nanophotonic substrate such that the dielectric layer is interposed between the nanophotonic substrate and the nanophotonic waveguide.

16. The optomechanical ultrasound detector of claim **1**, further comprising a meta-optic disposed on the micromirror substrate in optical communication with the micromirror substrate and that receives the initial laser light, communicates the initial laser light to the micromirror substrate, and receives the cavity output light from the micromirror substrate,

wherein the micromirror substrate is interposed between the meta-optic and the optical microcavity.

17. The optomechanical ultrasound detector of claim **1**, further comprising a piezoelectric ultrasound source disposed on a resonator substrate on which the mechanical resonator is disposed and that produces a probe ultrasound wave that is communicated from the optomechanical ultrasound detector to an object, such that the objects reflects the probe ultrasound wave as the ultrasound waves received by the mechanical resonator.

18. A process for performing ultrasound imaging with a optomechnical ultrasound detector, the process comprising:

receiving ultrasound waves by a mechanical resonator of a optomechanical ultrasound detector, the optomechanical ultrasound detector comprising:

a micromirror substrate;

a mechanical resonator disposed on the micromirror substrate, in optical communication with the micromirror substrate, spaced apart from the micromirror substrate at a cavity length L_c; and

an optical microcavity optically interposed between the micromirror substrate and the mechanical resonator and comprising the cavity length L_c with cavity resonance frequency f_c formed by optically opposing surfaces of the mechanical resonator and the micromirror substrate;

oscillating the mechanical resonator at a resonator frequency f_r in response to receiving the ultrasound waves;

changing the cavity length L_c of the optical microcavity based on oscillation of the mechanical resonator at resonator frequency f_r;

communicating initial laser light from the micromirror substrate to the mechanical resonator;

receiving, by the mechanical resonator, initial laser light from the micromirror substrate;

producing, by the mechanical resonator, intra-cavity light from the initial laser light;

optically encoding, by the mechanical resonator, in the cavity output light information about the ultrasound waves received by the mechanical resonator;

repeatedly communicating the intra-cavity light between the micromirror substrate and the mechanical resonator across the cavity length L_c when the intra-cavity light is resonant with the cavity resonance frequency f_c;

communicating the intra-cavity light from the mechanical resonator to the micromirror substrate; and

producing, by the micromirror substrate, cavity output light from the intra-cavity light to perform ultrasound imaging.

19. The process for performing ultrasound imaging of claim **18**, further comprising communicating the cavity output light from the micromirror substrate to an analyzer.

20. The process for performing ultrasound imaging of claim **19**, further comprising, performing by the analyzer;

receiving the cavity output light;

analyzing the cavity output light; and

determining the information about the ultrasound waves from analyzing the cavity output light.

* * * * *