the context of conventional, piezoelectric ultrasound sensors.

[0006] Photonic devices (e.g., gratings, etalons, etc.) and optical pressure detection techniques have shown great promise for ultrasound detection, and have gained increasing interest because these devices can be fabricated in micro-scales without sacrificing ultrasound detection performance or sensitivity. In photonic devices, refractive index modulation and/or shape deformations due to strain induced by an acoustic wave are translated into changes in the intensity of the detected light or the spectral properties of the device. In some existing devices, optical resonators have been used as highly sensitive ultrasound detectors. In these resonators, arrival of ultrasound wave leads to modulation of the resonant frequency or the transmitted light intensity. In general, the performance of an optical resonator is limited by its quality factor Q (i.e., the higher the Q, the lower the optical loss and the smaller the detectable resonance shift) as well as by the acousto-optical and mechanical properties of the material from which the resonator is made.

[0007] Other objects and features will be in part apparent and in part pointed out hereinafter.

BRIEF DESCRIPTION OF THE DISCLOSURE

[0008] In one aspect, an acoustic sensor is disclosed that includes an optical whispering gallery mode resonator, a coupling waveguide for optically coupling to the resonator, and a polymer encasing a portion of the coupling waveguide and the resonator. The coupling waveguide is spaced from the resonator by a separation gap. The polymer has a dimension engineered to enhance acoustic focus on the optical whispering gallery mode resonator. The resonator and the coupling waveguide each have higher refractive indices than the corresponding refractive index of the polymer. The dimension engineered to enhance the acoustic focus is an upper boundary of the polymer being a convex upper boundary.

[0009] In other aspects, an acoustic sensing system is disclosed that includes an optical whispering gallery mode resonator, a coupling waveguide for optically coupling to the resonator, a polymer encasing the resonator and a portion of the coupling waveguide, a light source coupled to the first end of the coupling waveguide projecting from the polymer, and a light detector coupled to the second end of the coupling waveguide and projecting from the polymer. The coupling

waveguide has a first end and a second end opposite the first end, and is spaced from the resonator by a separation gap. The polymer has a dimension engineered to enhance acoustic focus on the optical whispering gallery mode resonator. The resonator and the coupling waveguide each have higher refractive indices than the corresponding refractive index of the polymer. The dimension engineered to enhance the acoustic focus is an upper boundary of the polymer being a convex upper boundary.

[0010] In additional aspects, a photoacoustic imaging device is disclosed that includes an acoustic sensor. The acoustic sensor includes an optical whispering gallery mode resonator, a coupling waveguide for optically coupling to the resonator, a polymer encasing the resonator and a portion of the coupling waveguide, a transducer light source coupled to the first end of the coupling waveguide projecting from the polymer, a transducer light detector coupled to the second end of the coupling waveguide opposite to the first end and projecting from the polymer, and a photoacoustic light source. The coupling waveguide has a first end and a second end opposite the first end, and the coupling waveguide is spaced from the resonator by a separation gap. The polymer has a dimension engineered to enhance acoustic focus on the optical whispering gallery mode resonator. The resonator and the coupling waveguide each have higher refractive indices than the corresponding refractive index of the polymer. The dimension engineered to enhance the acoustic focus is an upper boundary of the polymer being a convex upper boundary.

[0011] In other additional aspects, a method for detecting ultrasound waves is disclosed that includes providing an acoustic sensing system. The acoustic sensing system includes an optical whispering gallery mode resonator, a coupling waveguide for optically coupling to the resonator, a polymer encasing the resonator and a portion of the coupling waveguide, a light source, and a light detector. The coupling waveguide has a first end and a second end opposite the first end, and the coupling waveguide is spaced from the resonator by a separation gap. The light source is coupled to the first end of the coupling waveguide projecting from the polymer, and the light detector couples to the second end of the coupling waveguide and projecting from the polymer. The polymer forms a sample contact surface and has a dimension engineered to enhance acoustic focus on the optical whispering gallery mode resonator. The resonator and the coupling waveguide each have higher refractive indices than the corresponding refractive index of the polymer. The dimension engineered to enhance the acoustic focus is an upper boundary of the polymer being a convex upper boundary. The method further includes acoustically coupling the sample contact surface with a sample such that ultrasound waves emitting from within the sample are conducted through the polymer to the resonator and the portion of the coupling waveguide, introducing light produced by the light source into the first end of the coupling waveguide, converting light from the second end of the coupling waveguide detected by

the light detector into detector signals encoding the amplitude of the detected light, and transforming the detector signals into a pressure using a predetermined calibration rule.

[0012] Other objects and features will be in part apparent and in part pointed out hereinafter.

CLAIMS

1. An acoustic sensor, comprising:

    an optical whispering gallery mode resonator;

    a coupling waveguide for optically coupling to the resonator, the coupling waveguide being spaced from the resonator by a separation gap; and

    a polymer encasing a portion of the coupling waveguide and the resonator, the polymer having a dimension engineered to enhance acoustic focus on the optical whispering gallery mode resonator;

    wherein the resonator and the coupling waveguide each have higher refractive indices than the corresponding refractive index of the polymer, and the dimension engineered to enhance the acoustic focus is an upper boundary of the polymer being a convex upper boundary.

2. The acoustic sensor of claim 1, wherein the separation gap is selected such that the acoustic sensor operates at an operating condition selected from critical coupling of the resonator and the coupling waveguide or at a maximum loading factor.

3. The acoustic sensor of claim 1, wherein the resonator comprises a diameter ranging from 50 μm to 200 μm.

4. The acoustic sensor of claim 1, wherein the separation gap ranges from 0.6 μm to 0.8 μm.

5. The acoustic sensor of claim 1, wherein the separation gap results in a maximum loading factor during operation of the acoustic sensor.

6. The acoustic sensor of claim 1, wherein the coupling waveguide is a tapered optic fiber with a minimum taper diameter of less than 1.5 μm.

7. The acoustic sensor of claim 1, wherein the acoustic sensor encodes pressure fluctuations as fluctuations in a transmission amplitude through the resonator.

8. The acoustic sensor of claim 1, wherein the polymer is a UV-curable polymer with a refractive index of 1.33.

9. An acoustic sensing system, comprising:

an optical whispering gallery mode resonator;

a coupling waveguide for optically coupling to the resonator, the coupling waveguide having a first end and a second end opposite the first end, the coupling waveguide being spaced from the resonator by a separation gap; and

a polymer encasing the resonator and a portion of the coupling waveguide, the polymer having a dimension engineered to enhance acoustic focus on the optical whispering gallery mode resonator;

a light source coupled to the first end of the coupling waveguide projecting from the polymer; and

a light detector coupled to the second end of the coupling waveguide and projecting from the polymer;

wherein the resonator and the coupling waveguide each have higher refractive indices than the corresponding refractive index of the polymer, and the dimension engineered to enhance the acoustic focus is an upper boundary of the polymer being a convex upper boundary.

10. The acoustic sensing system of claim 9, further comprising a driving system having a computing device with a processor, the driving system being operatively coupled to the light source and the light detector, wherein the driving system is configured to:

obtain a transmission spectrum by operating the light source at a range of wavelengths and receiving a plurality of detector signals from the light detector, the detector signals encoding the transmission of light from the light source through the coupling fiber coupled to the resonator;

select an operating wavelength for detecting pressure fluctuations based on the transmission spectrum; and

select the separation gap based on at least one transmission spectrum; and

detect pressure fluctuations by operating the light source at the operating wavelength and receiving a second plurality of signals from the light detector.

11. The acoustic sensing system of claim 10, wherein the acoustic sensor encodes pressure fluctuations as fluctuations in transmission amplitude through the optical whispering gallery mode resonator.

12. An ultrasound imaging device, comprising:

an acoustic sensor comprising:

an optical whispering gallery mode resonator;

a coupling waveguide for optically coupling to the resonator, the coupling waveguide having a first end and a second end opposite the first end, the coupling waveguide being spaced from the resonator by a separation gap;

a polymer encasing the resonator and a portion of the coupling waveguide, the polymer having a dimension engineered to enhance acoustic focus on the optical whispering gallery mode resonator;

a light source coupled to the first end of the coupling waveguide projecting from the polymer; and

a light detector coupled to the second end of the coupling waveguide opposite to the first end and projecting from the polymer;

wherein the resonator and the coupling waveguide each have higher refractive indices than the corresponding refractive index of the polymer, and the dimension engineered to enhance the acoustic focus is an upper boundary of the polymer being a convex upper boundary.

13. The ultrasound imaging device of claim 12, wherein the acoustic sensor encodes pressure fluctuations as fluctuations in a transmission amplitude through the resonator.

14. The ultrasound imaging device of claim 12, wherein the acoustic sensor is configured to detect ultrasound pulses generated within a region of interest in response to excitatory ultrasound pulses directed into the region of interest by an ultrasound transducer.

15. A photoacoustic imaging device, comprising:

an acoustic sensor comprising:

an optical whispering gallery mode resonator;

a coupling waveguide for optically coupling to the resonator, the coupling waveguide having a first end and a second end opposite the first end, the coupling waveguide being spaced from the resonator by a separation gap;

a polymer encasing the resonator and a portion of the coupling waveguide, the polymer having a dimension engineered to enhance acoustic focus on the optical whispering gallery mode resonator;

a transducer light source coupled to the first end of the coupling waveguide projecting from the polymer;

a transducer light detector coupled to the second end of the coupling waveguide opposite to the first end and projecting from the polymer; and

a photoacoustic light source;

wherein the resonator and the coupling waveguide each have higher refractive indices than the corresponding refractive index of the polymer, and the dimension engineered to enhance the acoustic focus is an upper boundary of the polymer being a convex upper boundary.

16. The ultrasound imaging device of claim 15, wherein the acoustic sensor encodes pressure fluctuations as fluctuations in a transmission amplitude through the resonator.

17. The ultrasound imaging device of claim 15, wherein the acoustic sensor is configured to detect photoacoustic signals generated within a region of interest in response to illumination by laser pulses produced by the photoacoustic light source.

18. A method for detecting ultrasound waves, the method comprising:

providing an acoustic sensing system, comprising:

an optical whispering gallery mode resonator;

a coupling waveguide for optically coupling to the resonator, the coupling waveguide having a first end and a second end opposite the first end, the coupling waveguide being spaced from the resonator by a separation gap; and

a polymer encasing the resonator and a portion of the coupling waveguide, the polymer further forming a sample contact surface, and the polymer having a dimension engineered to enhance acoustic focus on the optical whispering gallery mode resonator;

a light source for coupling to the first end of the coupling waveguide projecting from the polymer; and

a light detector for coupling to the second end of the coupling waveguide and projecting from the polymer;

wherein the resonator and the coupling waveguide each have higher refractive indices than the corresponding refractive index of the polymer, and the dimension engineered to enhance the acoustic focus is an upper boundary of the polymer being a convex upper boundary;

acoustically coupling the sample contact surface with a sample such that ultrasound waves emitting from within the sample are conducted through the polymer to the resonator and the portion of the coupling waveguide;

introducing light produced by the light source into the first end of the coupling waveguide;

converting light from the second end of the coupling waveguide detected by the light detector into detector signals encoding the amplitude of the detected light; and

transforming the detector signals into a pressure using a predetermined calibration rule.