High sensitivity air-coupled MHz frequency ultrasound detection using an on-chip microtoroid cavity

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Cavity optomechanical systems provide an ideal platform for ultrasound sensing, due to its dual-resonance enhanced sensitivity. Here we realize high sensitivity air-coupled ultrasound sensing in the megahertz (MHz) frequency range, using a microtoroid cavity. Benefitting from both the high optical Q factor (∼10^7) and mechanical Q factor (∼700), we achieve sensitivity of 46 μPa/Hz^{1/2} - 10 mPa/Hz in a frequency range of 0.25-3.2 MHz. Thermal-noise-limited sensitivity is realized around the mechanical resonance at 2.56 MHz, in a frequency range of 0.6 MHz. We also observe the second- and third-order mechanical sidebands, when driving the microcavity with an ultrasonic wave at the mechanical resonance and quantitatively study the intensities of each mechanical sideband as a function of the mechanical displacement. Measuring the combination of signal to noise ratios at all the sidebands has the potential to extend the dynamic range of displacement sensing.

I. INTRODUCTION

High-sensitivity ultrasound sensors are key components in various applications, such as medical diagnostics [1], photoacoustic imaging and spectroscopy [2,3], nondestructive testing [4], sonar [5,6], and trace gas monitoring [7,8]. Currently, the piezoelectric transducers represent the state-of-the-art ultrasound sensors, but achieving high sensitivity usually requires millimeter to centimeter sized sensors [3,11]. In order to realize both high sensitivity and spatial resolution, photonic ultrasound sensors that can be microfabricated on a silicon chip have been developed. Among them, cavity optomechanical systems [12,15] have attracted increasing interest, due to their high sensitivity, broad bandwidth, low power consumption, and capability for integration. In cavity optomechanical systems, displacement of the cavity can be optically read out, via the optomechanical coupling. As the response is enhanced by the mechanical resonance, and the readout sensitivity is enhanced by the optical resonance, cavity optomechanical systems provide an ideal sensing platform for displacement [16,17], mass [18,20], force [21,23], acceleration [24,25], magnetic field [26,32], and acoustic wave [33,47], etc.

Acoustic sensing using cavity optomechanical systems in the liquid environment have been demonstrated in various microcavity systems. Polymer materials are generally soft and can be easily deformed by acoustic waves, and therefore provide large sensing signals. Various polymer microcavities such as polystyrene [23,34], SU8 [35] and polydimethylsiloxane (PDMS) [36], have been fabricated for ultrasound sensing, and achieved sensitivity at Pascal level and high bandwidth of tens-to-hundreds of MHz. A Fabry-Perot cavity has been fabricated at the end of an optical fiber using UV curable epoxy, which has realized a sensitivity of mPa/Hz^{1/2} at the tens of MHz frequency range [37]. Silicon microcavities have also attracted increasing interest, as they can be massively produced on a chip and their fabrication techniques have been well developed in the past few decades. Recently, Shnaiderman et al. demonstrated miniaturized high-sensitivity ultrasound sensing using an array of point like silicon waveguide-etalon detector on a silicon on insulator (SOI) platform, and realized a bandwidth of hundreds of MHz [38]. Later, Westerveld et al. demonstrated an optomechanical ultrasound sensor using a silicon microring cavity coupled with a thin film, with a 15 nm gap in between, and realized a sensitivity of mPa/Hz^{1/2} in the tens of MHz frequency range [39]. Silica microcavities have also been extensively explored for ultrasound sensing, due to their ultrahigh optical Q factors. Ultrasound sensing in a liquid environment has been demonstrated using a microtoroid cavity encapsulated in polymer [40], and a microsphere cavity [34,41].

Air-coupled ultrasound sensing has specific applications such as gas photoacoustic spectroscopy [48], and non-contact ultrasonic medical imaging [49]. Due to the large impedance mismatch at the acoustic source/air interface and the absorption loss of ultrasonic waves, air-coupled ultrasound detection requires ultrahigh sensitivity. Ultrasound sensing in air has been demonstrated using microbottle cavities, with sensitivities on the order of mPa/Hz^{1/2} at tens to hundreds of kHz frequency range [42,43]. Through detecting the acoustic wave induced modulation of the Brillouin laser in a microsphere, acoustic sensitivity of 267 μPa/Hz^{1/2} has been realized in the kHz frequency range [44]. Basiri-Esfahani et al. have re-
In our detection system, the main sources of noise are optical shot noise and mechanical thermal noise. For a microcavity with optical loss rate of $\kappa$ and mechanical damping rate of $\gamma$, the corresponding noise equivalent pressure can be expressed as Eq. (1) [45]:

$$P_{\text{min}}(\omega) = \frac{1}{r\zeta A} \sqrt{\frac{\kappa}{16\eta N G^2|\chi_n|}} [1 + 4(\frac{\omega}{\kappa})^2] + 2m\gamma k_B T$$

(1)

where $r$ is the ratio of pressure difference between the upper and lower surfaces of the device to the peak pressure, as the toroid cavity only moves by feeling the pressure difference between the upper and lower surfaces. $\zeta$ is the spatial overlap between the incident ultrasound and the mechanical displacement profile of the sensor. $\omega$ is the angular frequency of the incident ultrasound wave, and $A$ is the sensor area. The first term under the square-root denotes shot noise [50], with $\eta$ being the total detection efficiency of light, and $N$ the number of photons in the cavity. $G = \omega/d\omega$ denotes the optomechanical coupling coefficient, quantifying the cavity frequency shift for unit mechanical displacement $x$. The second term under the square-root quantifies thermal noise at temperature $T$, introduced by both the intrinsic damping of the mechanical resonator and collisions with the gas molecules around the sensor. Here $m$ is the effective mass of the sensor, and $\chi_n(\omega)$ is the mechanical susceptibility, quantified by

$$\chi_n(\omega) = \frac{1}{m(\omega_m^2 - \omega^2 - \gamma_m^2)},$$

with $\omega_m$ being the angular frequency of the mechanical resonance. From the equation (1), we can see that the sensitivity is fundamentally limited by the thermal noise, if the measurement strength is strong enough to enable thermal noise dominating shot noise. As a result, reaching thermal-noise-limited regime is beneficial to achieving a better sensitivity. This can be realized by increasing the optical $Q$ factor, mechanical $Q$ factor, and the optomechanical coupling coefficient. A larger sensing bandwidth can be obtained by increasing the thermal noise dominant frequency range.

The first-order flapping mode, with its displacement profile shown in Fig. 3(a), has a large spatial overlap with the ultrasonic wave coming from the top of the sensor, which is beneficial to achieving a good ultrasound sensitivity. We then optimize the ultrasound sensitivity for this mode, by changing the geometric parameters of the toroid. We first simulate the resonance frequency for this mode, by changing the geometric parameters of the toroid. We first simulate the resonance frequency for this mode, by changing the geometric parameters of the toroid. We then simulate the resonance frequency and calculate the corresponding sensitivity for different principal diameters of the disk. It can be seen that, with the increase of the principal diameter, the resonance frequency of the mechanical resonance, which is caused by the transduction nonlinearity. We measure the signal-to-noise ratios (SNRs) under different ultrasound pressures ($P$), and find that $\sqrt{\text{SNR}}$ of the first-, second-, and third-order mechanical sidebands is approximately proportional to $P$, $P^2$, and $P^3$, respectively, which agrees well with our theoretical results.

II. METHODS

The ultrasound sensitivity is determined by the noise in the sensor. In our detection system, the main sources of the sensor. Here $m$ is the effective mass of the sensor, and $\chi_m(\omega)$ is the mechanical susceptibility, quantified by

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The first-order flapping mode, with its displacement profile shown in Fig. 3(a), has a large spatial overlap with the ultrasonic wave coming from the top of the sensor, which is beneficial to achieving a good ultrasound sensitivity. We then optimize the ultrasound sensitivity for this mode, by changing the geometric parameters of the toroid. We first simulate the resonance frequency for different principal diameters of the cavity from 30 to 1000 $\mu$m, with the result shown in Fig. 4(a). In the simulation, we keep the minor diameter of the toroid to be 6 $\mu$m, and the disk thickness to be 2 $\mu$m. It can be seen that, with the increase of the principal diameter, the sensitivity increases monotonously. We then calculate the ultrasound sensitivity for different principal diameters of the toroid, with the result shown in Fig. 4(b). In the calculation, we use the optical $Q$ factor of $10^7$ and the mechanical $Q$ factor of 700, obtained from our experiment. It can be seen that with the increase of the principal diameter, the sensitivity gets better, due to the increased sensing area. We then simulate the resonance frequency and calculate the corresponding sensitivity for different
FIG. 2. (a) SEM image of the microtoroid cavity, with the inset showing the simulated optical field distribution of the fundamental WGM. (b) Top-view optical microscope image of the microtoroid cavity. $D_\text{principal}$, $D_\text{major}$, and $D_\text{minor}$ denote the principal diameter, major diameter, and minor diameter of the microtoroid, respectively, with $D_\text{principal} = D_\text{major} + D_\text{minor}$. The scale bars in (a) and (b) both correspond to 10 μm. (c) The transmission spectrum of the cavity around 1550 nm, with the red solid curve showing the double Lorentzian fitting result, from which we can obtain $Q_{\text{im}} \approx 10^7$. (d) Schematic diagram of the experimental setup for ultrasound sensing. PD, photodetector; VNA, vector network analyzer; OSC, oscilloscope; ESA, electronic spectrum analyzer.

Disk thicknesses from 200 nm to 5 μm, with the results shown in Figs. 1(c) and 1(d), respectively. It can be seen that, with the disk thickness increases, the resonance frequency increases, and the sensitivity gets worse. This means having a larger principal diameter and a thinner disk is beneficial to improving the ultrasound sensitivity.

In our experiment, in order to optimize the ultrasound sensitivity at MHz frequency range, we choose a toroid with a principal diameter of ~57 μm, minor diameter of ~6 μm, whose mechanical resonance frequency of the first-order flapping mode is ~2.56 MHz and corresponding effective mass is 14.1 ng. In order to facilitate the fabrication of high optical $Q$ toroid, we choose the disk thickness to be 2 μm instead of a thinner one. For an ideal case, $\zeta = 1$, $r = 1$, the corresponding sensitivity is calculated to be ~16.6 μPa/Hz$^{1/2}$.

The microtoroid cavity is fabricated by standard micro-fabrication processes [51] from a silica-on-silicon wafer, including photolithography, hydrofluoric acid (HF) wet etching, xenon difluoride (XeF$_2$) dry etching, and a CO$_2$ laser reflow process. After the reflow process, we perform a second XeF$_2$ dry etching process to obtain a thin silicon pedestal of ~5 μm in diameter. This can decrease the mechanical energy dissipation from the toroid to the substrate, and therefore enable higher mechanical $Q$. Figure 2(a) shows a scanning electron microscope (SEM) image of the microtoroid. The inset of Fig. 2(a) shows the simulated optical field distribution of a fundamental whispering gallery mode (WGM), where the optical field is confined around the periphery of the microtoroid. Figure 2(b) shows the top-view optical microscope image of the microtoroid cavity.

The measurement setup for ultrasound sensing using the microtoroid is shown in Fig. 2(d). Light from a tunable laser in the 1550 nm wavelength band is coupled into the WGM of the microtoroid, through a tapered fiber [52]. The transmitted light from the tapered fiber is detected by a photodetector, and monitored by an oscilloscope. The measured transmission spectrum for one WGM ~1550 nm is shown in Fig. 2(c). We can see a mode splitting, which is caused by the backscattering from the surface roughness of the cavity. From the double-peak Lorentzian fitting (the red curve), we can derive the intrinsic linewidth of the mode to be $\Delta \lambda = 0.16$ pm (or $\approx 2\pi/19.4$ MHz in frequency), corresponding to an intrinsic optical $Q$ factor of about $10^7$. This optical $Q$ factor allows a 3dB bandwidth of 16.8 MHz, considering the frequency dependence of the shot noise.

The principle of ultrasound detection is shown in the inset of Fig. 2(d). When an ultrasonic wave is applied to the sensor, it can drive the mechanical motion of the cavity and induce a change in the cavity circumference or the taper-cavity coupling strength. Both translate into an amplitude modulation of the intracavity field, which can be optically readout. In our experiment, we use a proportional–integral–derivative (PID) controller to lock the laser wavelength on the side of the optical mode with a detuning where the transmission has the largest slope, to optimize the dispersive transduction of ultrasound signal. The mechanical spectrum of the microcavity is measured with an electronic spectrum analyzer (ESA). The ultrasound signal is produced by an ultrasonic transducer. We use a function generator to apply a single-frequency sinusoidal voltage to the transducer to measure the single-frequency response of the sensor, and use a vector network analyzer (VNA) to sweep the frequency of the applied ultrasonic wave to obtain the system response.

To obtain the sensitivity in a broad frequency range, we use two ultrasonic transducers with center frequencies at 1 MHz and 5 MHz, respectively. Considering the attenuation of ultrasonic wave in air, the relation between the ultrasound pressure at the sensor ($P_{\text{sensor}}$) and that at the ultrasonic transducer ($P_{\text{PZT}}$) is $P_{\text{sensor}}(\omega) = e^{-\alpha \omega d} P_{\text{PZT}}(\omega)$, where $d$ is the distance between the ultrasonic transducer and the sensor, which is kept to be ~1 cm in our experiment. $\alpha$ is the acoustic attenuation coefficient, which is obtained by the Stokes-Kirchhoff formula [53, 54].
\[ \alpha = \frac{\omega^2}{2 \rho c^2 \frac{1}{3} \eta' + \left( \frac{1}{C_v} - \frac{1}{C_p} \right)} \]  

where \( \rho \) is the density, \( c \) is the speed of sound, \( \eta' \) is the dynamic viscosity coefficient, \( C_v \) and \( C_p \) are the specific heat capacities at constant volume and constant pressure, respectively. From this formula, we can see that the absorption loss is proportional to the square of frequency, which makes high frequency ultrasound sensing in air challenging. The ultrasound pressure at the ultrasonic transducer is calibrated using a hydrophone. We measure the pressure of the ultrasound produced by the transducer in water at different frequencies with the hydrophone, and then derive the pressure in air, taking into account the acoustic impedance mismatch, \( P_{\text{air}} = P_{\text{water}} \cdot \frac{Z_{\text{water}}}{Z_{\text{air}}} = \frac{P_{\text{water}}}{\rho c} \), where \( \rho c \) is the acoustic impedance of the material.

III. RESULTS

The noise power spectrum measured from the ESA is shown in the black solid curve in Fig. 3(a), in which we can see a mechanical resonance at 2.56 MHz. This corresponds to a first-order flapping mode, with its mode profile shown in the inset. The thermal noise, shot noise, and total noise in the frequency range of 2-3.2 MHz, calculated from Eq. (1), are shown in the orange dashed curve, blue short-dashed curve, and red dash-dotted curve in Fig. 3(a). From the linewidth of the resonance, we can obtain the mechanical \( Q \) factor of this mode to be \( \sim 700 \). The corresponding displacement power spectral density \( S_{xx}(\Omega) \) of the sensor is shown on the right axis of Fig. 3(a). When we apply an ultrasound signal with a pressure \( P_{\text{applied}} = 132.2 \text{ mPa} \) at 2.56 MHz, we obtain a SNR of 41.39 dB, measured with a resolution bandwidth \( \Delta f = 20 \text{ Hz} \), with the result shown in the green solid curve in Fig. 3(a). The sensitivity at 2.56 MHz can be calculated by the following equation.

\[ P_{\text{min}}(\Omega) = \frac{P_{\text{applied}}(\Omega)}{\sqrt{\frac{1}{\text{SNR}} \cdot \frac{1}{\Delta f}}} \sim 252 \mu \text{Pa/Hz}^{1/2} \]  

Using the parameters in our experiment, we can obtain the pressure different of the sensor from simulation, to be \( r = 0.237 \) at 2.56 MHz. Considering that the angle \( \theta \) between the incident ultrasonic wave and the disk surface to be 30°, the spatial overlap \( \zeta = \sin \theta = 0.5 \). We can derive the theoretical sensitivity at this frequency to be 169 \( \mu \text{Pa/Hz}^{1/2} \), which is close to our experimental result.

We then use a network analyzer to drive the ultrasonic transducer to obtain the system response of our sensor, for ultrasonic waves at different frequencies. In order to obtain the sensor response in a broad frequency band, we use two ultrasonic transducers, with center frequencies at 1 MHz and 5 MHz, respectively. System response in the frequency range of 0.25-3.2 MHz is obtained, with the result shown in Fig. 3(b). The lower frequency limit of 0.25 MHz is not intrinsic, but rather limited by the low pressure of the ultrasound produced by the transducer. The upper limit of 3.2 MHz is introduced by the larger attenuation of air at higher frequencies. It can be seen that the response of the sensor around the resonance frequency of 2.56 MHz is significantly enhanced, due to the high mechanical \( Q \) factor of the mode and the large spatial overlap between the mode displacement and the ultrasonic wave. Other peaks in the frequency band correspond to other mechanical modes of the toroid or the tapered fiber. These modes do not reach thermal noise dominant regime, and are therefore not seen in the noise.
power spectrum in Fig. 3(a).

From the system response \( S(\omega) \) and the noise power spectral density \( N(\omega) \), combining with the sensitivity \( P_{\text{min}}(\Omega) \) at \( \Omega/2\pi = 2.56 \text{ MHz} \), we can derive the sensitivity over the entire frequency range:

\[
P_{\text{min}}(\omega) = P_{\text{min}}(\Omega) \frac{P_{\text{applied}}(\omega)}{P_{\text{applied}}(\Omega)} \sqrt{\frac{N(\omega)}{N(\Omega)}} \frac{S(\Omega)}{S(\omega)} \tag{4}
\]

where \( P_{\text{applied}}(\omega) \) is the applied ultrasound pressure at different frequencies. The sensitivity in the frequency range of 0.25-3.2 MHz is shown in Fig. 3(c), and the corresponding force sensitivity is shown on the right axis. A peak pressure (force) sensitivity of 46 \( \mu \text{Pa}/\text{Hz}^{1/2} \) (118 \( \text{fN}/\text{Hz}^{1/2} \)) is achieved at 0.29 MHz. Around the mechanical resonance frequency, thermal-noise-limited sensitivity is reached in the frequency range of 2.24-2.84 MHz, with pressure (force) sensitivities of 130-475 \( \mu \text{Pa}/\text{Hz}^{1/2} \) (0.34-1.21 pN/Hz\(^{1/2} \)). In the whole frequency range of 0.25-3.2 MHz, the pressure (force) sensitivity is better than 10 mPa/Hz\(^{1/2} \) (26.4 pN/Hz\(^{1/2} \)). In terms of force sensitivity, the peak sensitivity of 118 \( \text{fN}/\text{Hz}^{1/2} \) of our sensor is about three times better than that in Ref. [45], and the sensitivity within 1 MHz frequency range is about one order of magnitude better than that in Ref. [45].

When we apply an ultrasound signal at the mechanical resonance frequency \( \Omega/2\pi = 2.56 \text{ MHz} \), in addition to a response peak at this frequency, we also observe responses at the second- and third-order mechanical sidebands, with the result shown in Fig. 3(a). It can be seen that, when the ultrasound pressure is on, three peaks at \( \Omega, 2\Omega, \text{ and } 3\Omega \) appear in the noise power spectrum. In our experiment, we keep the input laser power to be as low as 10 \( \mu \text{W} \) to avoid the backaction noise form the input light. In this case, the radiation pressure force induced mechanical oscillations can be neglected, and the higher order mechanical sidebands are induced by the nonlinear transduction. Since the cavity mode is a Lorentzian lineshape, the optical readout signal for displacement is a harmonic oscillation only for a small displacement. In the large displacement case, the readout signal becomes anharmonic. Previous works have experimentally studied the intensity of the high order mechanical sidebands as a function of the optical power [55, 57], and theoretically studied the dependence of the high order mechanical sidebands on the displacement [61]. Here we experimentally study the intensity of the high order mechanical sidebands with different mechanical displacements, driven by an ultrasonic wave. We measure the SNR at the first-, second-, and third-order sidebands, with the results shown in the black squares, red circles, and blue triangles, respectively, in Fig. 3(b). By performing an exponential fitting to these experimental results, we obtain that \( \sqrt{\text{SNR}(\Omega)} \propto P^{1.13}, \sqrt{\text{SNR}(2\Omega)} \propto P^{1.90}, \sqrt{\text{SNR}(3\Omega)} \propto P^{1.04} \).

In the following we theoretically study the dependence of SNR at the three sidebands on the ultrasound pressure. From the equation of motion of the cavity mode \( \hat{a} = -\kappa \hat{a} + \Delta \hat{a} + 2\sqrt{\kappa_e \epsilon} \), we can obtain the intracavity photon number to be \( n = \frac{2\kappa_e \epsilon}{\Delta^2} \), with \( s \) being the number of photons injected into the microcavity per unit time, and \( \kappa = \kappa_0 + \kappa_e \) being the total loss of the cavity. \( \kappa_0 \) is the intrinsic loss of the cavity mode, and \( \kappa_e \) is the coupling loss induced by the tapered fiber. \( \Delta = \Delta/\kappa \) is the dimensionless detuning, with \( \Delta = \omega - \Omega_0 \) denoting the frequency detuning between the input light and the cavity mode. Taylor expanding the detuning \( \delta \), we can obtain the intracavity photon number to be:

\[
n \approx n_{\text{max}} [c_0(\delta) + c_1(\delta)u + c_2(\delta)u^2 + c_3(\delta)u^3] \tag{5}
\]

where \( c_0(\delta) = 1/(1+\delta^2) \), \( c_2(\delta) = 1/\delta^2 \), \( c_0(\delta) \), and \( u = Gx/\kappa \) represents the normalized frequency shift of the cavity mode caused by the mechanical displacement. Using the input-output relation, we can obtain the photocurrent arriving at the photodetector at a certain detuning:
Z = |z|^2 \approx s - \frac{4\kappa_0 k_0 s}{k^2} c_0(\delta) + c_1(\delta) \frac{G}{\kappa} x + c_2(\delta) \left( \frac{G}{\kappa} \right)^2 x^2 + c_3(\delta) \left( \frac{G}{\kappa} \right)^3 x^3

Expressing the displacement of the cavity caused by the ultrasonic wave with \( x = x_0 \cos(\Omega t) \), we can obtain the following coefficients of the photocurrent for DC, \( \Omega \), 2\( \Omega \), and 3\( \Omega \) frequency components:

\[
Z_{DC} = s - \frac{4\kappa_0 k_0 s}{k^2} c_0(\delta) \tag{7}
\]

\[
Z_{\Omega} = -\frac{4\kappa_0 k_0 s}{k^2} c_1(\delta) \frac{G}{\kappa} x_0 \cos(\Omega t) \tag{8}
\]

\[
Z_{2\Omega} = -\frac{4\kappa_0 k_0 s}{k^2} \left[ c_2(\delta) \left( \frac{G}{\kappa} \right)^2 \frac{x_0^2}{2} \cos(2\Omega t) \right] \tag{9}
\]

\[
Z_{3\Omega} = -\frac{4\kappa_0 k_0 s}{k^2} \left[ c_3(\delta) \left( \frac{G}{\kappa} \right)^3 \frac{x_0^3}{4} \cos(3\Omega t) \right] \tag{10}
\]

As the amplitude of the mechanical displacement \( x_0 \) is proportional to the ultrasound pressure \( P \), we can obtain the dependence of SNR on the ultrasound pressure \( P \) at the three mechanical sidebands are \( \sqrt{\text{SNR}(\Omega)} \propto P \), \( \sqrt{\text{SNR}(2\Omega)} \propto P^2 \), \( \sqrt{\text{SNR}(3\Omega)} \propto P^3 \), respectively, which can explain our experimental results well. Measuring the combination of SNRs at all the mechanical sidebands has the potential to extend the sensing dynamic range of displacement sensing.

IV. DISCUSSION

In summary, we have proposed and demonstrated a scheme for air-coupled high-sensitivity MHz frequency ultrasound detection. We have fabricated an on-chip microtoroid cavity with a thin pedestal to obtain both high optical and mechanical \( Q \) factors. We have achieved air-coupled ultrasound detection in the MHz band, with a frequency range from 0.25 MHz to 3.2 MHz, with the sensitivities of 46 \( \mu \text{Pa}/\text{Hz}^{1/2} \)-10 \( \mu \text{Pa}/\text{Hz}^{1/2} \). This work broadens the frequency range of air-coupled ultrasound sensing using cavity optomechanical systems and obtains a wide thermal noise dominant regime. By using the first-order flapping mode at 2.56 MHz, which has a great spatial overlap with the ultrasonic wave coming from the top of the sensor, combining with the high optical and mechanical \( Q \) factors, we have achieved thermal-noise-limited sensitivities of 130-475 \( \mu \text{Pa}/\text{Hz}^{1/2} \) in a frequency range of 0.6 MHz. In addition, we have observed the second- and third-order mechanical sidebands when driving the sensor with an ultrasound at the mechanical resonance frequency, and measured the intensities at the three mechanical sidebands, with the results consistent with our theoretical results. This nonlinear transduction provides a way to extend the dynamic range of displacement sensing.

The ultrasound sensitivity can be further improved by using a larger and thinner cavity, realizing a larger pressure difference ratio \( r \) by designing the structure, and optimizing the incident angle of the ultrasound. The use of mechanical modes with stronger optomechanical coupling coefficient \([17]\) and squeezed light \([31]\) can reduce shot noise and expand the thermal noise dominant regime. Integrated waveguide-coupled microcavities \([61]\) and on-chip arrays of sensors can be used in the future, for photoacoustic imaging and spectroscopy \([2,4]\). This work broadens the frequency range of ultrasound detection in air, which is of great significance for applications in gas photoacoustic spectroscopy, and non-contact ultrasonic medical imaging, etc. The photoacoustic signal near the resonance frequency has an enhanced response, which can be applied to high-sensitivity biomedical measurements \([48,49]\).

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