High-resolution temperature measurement is nerve-wracking obstruction for precise characterization of many physical, chemical, and biological processes. To solve this problem, a novel microcavity–optomechanical–oscillation-based thermometer is proposed. The microcavity serving as a link parametrically couples the mechanical resonator and optical resonator in the same structure and provides a natural and highly sensitive temperature transduction mechanism and ultrahigh-resolution optical demodulation. The mathematical model of geometrical parameters, mechanics, and material properties for temperature response mechanism is established and verified experimentally. The proposed thermometer has a thermal sensitivity of $11300\text{ Hz} \cdot \text{C}^{-1}$ and an ultrahigh-temperature resolution of $1 \times 10^{-4} \text{ C}$, to the best of one’s knowledge, which is the highest temperature resolution with a silica cavity.

1. Introduction

Temperature is a fundamental physical property for characterizing many reactions or states in physical, biological, and chemical processes. High-resolution temperature-sensing provides a powerful boost in many fields. For instance, precise and continuous monitoring of temperature changes in the ocean is critical for understanding the thermal phenomenon and providing essential observations to improve climate models, such as dynamic ocean circulation\textsuperscript{[10]} or suppression of global warming.\textsuperscript{[9]} Another example is that the friction dissipates heat during an earthquake, the fault temperature after an earthquake provides insight into the level of friction and controls earthquake dynamics.\textsuperscript{[1,4]} The resolution of temperature sensing in ocean and geological changes needs to be order of at least $10^{-3} \text{ C}$.\textsuperscript{[2,3]} In addition, semiconductor industry,\textsuperscript{[5,6]} biology, medicine,\textsuperscript{[7–10]} and energy harvesting\textsuperscript{[11,12]} also require ultrahigh-temperature resolving ability.

Various thermal-sensing methods based on optical fiber sensors are developed due to its electromagnetic immunity and electrical passive, such as fiber Bragg gratings and fiber Fabry–Perot interferometers. However, the requirement of high resolution is not well resolved. Optical resonant cavities\textsuperscript{[13]} provide a good platform solution. Especially, the whispering gallery mode (WGM) resonators\textsuperscript{[14,15]} can provide high Q value and strong light–matter interaction, consequently improving resolution. The temperature variation induces a change in the cavity optical path, which causes the sharp resonant dips to move. Temperature variation information is obtained by tracking the resonant wavelengths shift or monitoring the patterns of multiple modes.\textsuperscript{[16]} Moreover, the use of multiple modes may realize simultaneous measurement of multiple parameters, such as a pair of cavity modes are used to decouple the refractive index and temperature information of the analyte during the phase-transition process.\textsuperscript{[17]} Starting from solid silica microcavities,\textsuperscript{[18]} organic materials microcavities,\textsuperscript{[19–21]} all-liquid microcavities,\textsuperscript{[22,23]} and hollow liquid core microcavities\textsuperscript{[24,25]} have been developed for temperature sensing. The advantages of organic material and liquid microcavities are their large thermal expansion coefficient and thermo-optical coefficient, so they have higher temperature sensitivity than silica microcavities. However, organic material microcavities\textsuperscript{[26]} show a slower response due to poor thermal conductivity. In addition, the consistency between heating and cooling cycle is worse due to large hysteresis essence of organic material. Liquid microcavities are difficult to manipulate and store, which prevent it from stable and long-term monitoring. Its large cavity optical loss also deteriorates the Q value and sensing resolution.

Recently, the cavity optomechanical systems\textsuperscript{[27,28]} have attracted increasing attention due to their enhanced interactions between light resonator mode and mechanical resonator mode in a single microcavity. WGM–resonator-based optomechanics\textsuperscript{[29–31]} have been used for many fundamental experiments including mesoscopic quantum mechanics studying,\textsuperscript{[32]} intrinsic cavity cooling,\textsuperscript{[33,14]} and chaotic quivering.\textsuperscript{[15]} The mechanical resonance can enhance response and optical resonance can enhance readout sensitivity with less detrimental noise,\textsuperscript{[36]} therefore cavity optomechanical systems have a nature essence of high-resolution transduction mechanism for bioparticles,\textsuperscript{[37]} viscous liquid
analysis,\textsuperscript{[38,39]} mass, and displacement.\textsuperscript{[40,41]} However, there are few explorations on temperature sensing using optomechanical oscillation. In fact, the previous researches also need to consider effect of tiny temperature fluctuation.

In this paper, we propose and experimentally demonstrate an ultrahigh-resolution optical fiber thermometer based on radiation–pressure-driven optomechanical oscillation on a hollow silica microbubble. The cavity serving as a link parametrically couples the mechanical resonator and optical resonator in the same structure, and provides a natural and highly sensitive temperature transduction mechanism and ultrahigh-resolution optical demodulation. A stable optomechanical oscillation with oscillation frequency of \( \approx 10 \text{ MHz} \) is generated on a self-made silica microbubble with outer diameter of \( \approx 100 \mu \text{m} \). The influences of geometrical parameters, mechanics, and material properties on temperature response mechanism are investigated theoretically and experimentally. The optical fiber thermometer is interrogated with electrical domain frequency shift of the theoreticallly and experimentally. The optical properties on temperature response mechanism are investigated in References of geometrical parameters, mechanics, and material properties in References of geometrical parameters, mechanics, and material properties.

Establishing a mechanical resonator analytic model will help the sensor design. However, it is hard to get an analytic mechanical solution for a complicated structure. Considering the tiny fiber taper being used to excite the microbubble vertically, outer diameter of microbubble is far larger than that of fiber taper and the axial dimension (\( \approx \text{cm} \)) of sensor is far larger than its transverse dimension (\( \approx 100 \mu \text{m} \)), and it will be a reasonable simplified model by approximating the sensor with cylindrical shell model. The breathing mode mechanical resonant frequency of the sensor can be described as\textsuperscript{[42–44]}

\[
f^2 = \frac{1}{4\pi^2 \rho H} \left\{ \frac{E H}{R^4} \left( \frac{\pi}{L} \right)^4 + D \left[ \frac{\pi}{L} \right]^2 \right\} + \frac{N_x}{\left( \frac{R}{\phi} \right)^2} + \frac{N_y}{\left( \frac{R}{\phi} \right)^2}
\]

(1)

where \( R \) is the outer radius, \( H \) is the wall thickness, and \( L \) is the distance between two UV glue points. \( E \) is the Young’s modulus and \( \rho \) is the mass density. \( n \) is the number of circumferential waves. \( D \) is bending stiffness factor, given by \( D = E \cdot H^2/12 (1 - \mu^2) \), \( \mu \) is the Poisson’s ratio. \( N_x \) and \( N_y \) are the axial and the circumferential resultant stresses, \( N_x = N_{x\phi} + N_{x\phi} \), \( N_y = N_{y\phi} \). When \( N_x = N_{y\phi} = 0 \), the resonant frequency is designated as initial frequency \( f_0 \). When the temperature changes, four dominating factors, that is, axial force variation \( \Delta F \) (through \( N_{x\phi} \)), external pressure variation \( \Delta P_{in} \) (through \( N_{x\phi} \) and \( N_{x\phi} \)), microbubble radius variation \( \Delta R \), and Young’s modulus variation \( \Delta E \) (silica Young’s modulus temperature coefficient \( \Delta E_s = 183 \text{ ppm °C}^{-1} \)\textsuperscript{[45]} will change mechanical resonant frequency of the sensor (see Figure 1a) and therefore its temperature response. The temperature sensitivity is given by \( S_T = (f - f_0)/\Delta T \).

There is large difference between the thermal expansion coefficient of copper sheet and that of silica, so we enhance the temperature response of the sensor greatly by fixing the both ends of microcapillary on copper sheet base to produce large thermal-induced stress. The axial force \( \Delta F \) will generate axial stress on the microbubble.

\[
N_{x\phi} = \frac{\left( a_{\text{cu}} - a_s \right) \Delta T A_{\text{cu}} E_{\text{cu}} E_{\text{si}}}{\left( A_{\text{si}} E_{\text{si}} + A_{\text{cu}} E_{\text{cu}} \right)}
\]

(2)

where \( A_{\text{si}} \) is the microbubble cross-sectional area.

Although the ends of microcapillary are not sealed, the flow resistance due to its small diameter makes the air unable to exhale out under small thermal-induced pressure difference. Thus, the internal pressure variation \( \Delta P_{in} \) is regulated by the Clapeyron equation \( P_{in} V/T = C_1 \) through thermal expansion and contraction of air inside the microbubble, where \( C_1 \) is constant. Since the silica thermal expansion coefficient is very small (\( \approx 0.5 \text{ ppm °C}^{-1} \)),\textsuperscript{[46]} we assume that the volume \( V \) is constant and obtain \( 1/T \cdot dP_{in}/dT = P_{in}/T^2 \cdot dT/dT = 0 \) by differentiating operation of Clapeyron equation, which result in \( \Delta P_{in} = P_{in}/T \cdot dT \). This effect is equivalent to the simultaneous change of axial and circumferential stress\textsuperscript{[41]}

2. Results

2.1. Principle of Temperature Sensing Based on Microcavity Optomechanical Oscillation

The temperature sensor comprises an ultrathin-wall microbubble formed on a silica microcapillary and fixed on a copper sheet by UV glue, as shown in Figure 1a. A microbubble works as a mechanical resonator and an optical resonator at the same time. The tiny temperature change will affect the mechanical-mode frequency through geometrical parameters, mechanics, and material properties of microbubble. The reading out mechanism of optomechanical oscillation is shown in Figure 1b,c. The microbubble supports an initial WGM resonance mode with optical frequency \( \omega_0 \). A continuous-wave optical input pump with optical frequency \( \omega \) (higher than \( \omega_0 \)) is coupled into the microbubble through a tapered fiber and generates radiation pressure, which expands the cavity structure and consequently decreases WGM optical frequency \( \omega_0 \), that is, spectral line with black color shifts to red one in Figure 1c. The WGM optical frequency \( \omega_0 \) shift to \( \omega_0' \) will cause larger optical loss and reduce circulating optical power in the microcavity, which in turn reduces radiation pressure and make microbubble restore the mechanical deformation. When positive feedback produced by the circulating optical power is large enough to overcome the mechanical loss, a periodic deformation motion or breathing mechanical oscillation of microbubble at mechanical eigenmode frequency \( f \) will be excited. The modulated output light shows the same amplitude modulation frequency \( f \) (Figure 1c inset). Thus, the temperature is reflected in output light-modulated frequency, which can be easily obtained from a low-cost electrical domain spectrometer or Fourier transfer of time–domain data acquisition. Figure 1d illustrates the opto-mechanical sensing path.
The microbubble radius change $\Delta R$ is affected by the silica thermal expansion and axial force $\Delta F$, which can be expressed with $\Delta R = R \cdot \alpha_b$, where $\alpha_b$ is the deformation factor that obtained by a comparison measurement experiment.

The microbubble radius change $\Delta R$ is affected by the silica thermal expansion and axial force $\Delta F$, which can be expressed with $\Delta R = R \cdot \alpha_b$, where $\alpha_b$ is the deformation factor that obtained by a comparison measurement experiment.

\[
N_{sb} = \Delta P_{in} \cdot R/2 \\
N_{gb} = \Delta P_{in} \cdot R
\]

\[
(3) \quad \alpha_b = \alpha_s - \frac{\Delta \lambda_s \Delta \lambda_b}{\lambda_s \Delta \lambda_b \Delta T}
\]

where $\alpha_s$ is the temperature deformation coefficient of single-ended fix microbubble, $\lambda_s$ is the optical WGM resonance–wavelength of single/both-ended fix microbubble, and $\Delta \lambda_s/\Delta \lambda_b$ is the spectrum change with temperature.
2.2. Experimental Setup

The wall-thickness-controlled microbubbles used in our experiment are fabricated from commercial fused silica capillary preforms that are tapered under heating with oxyhydrogen flame (see details in Experimental Section). The microbubble used in double clamped sensor has an outer radius of 103 μm and a wall thickness of 1.70 μm (Figure 2a inset), where acoustic and optical modes are simultaneously confined. The temperature sensor is placed on a heating station with high precision temperature controller. Figure 2a illustrates the experimental setup for temperature sensing of these hollow-shell oscillators. This system is used to verify the sensing principle, and the subsequent application only needs C-band laser pumping and demodulation by the data acquisition card. The light from a tunable laser (Keysight 81607 A, linewidth: <10 kHz, tunable range: 1500–1600 nm) is coupled into the microbubble by a tapered optical fiber. Light is evanescently coupled into the WGM mode of microbubble resonator. The input optical power ranges from 1 to 5 mW. The tapered fiber was fabricated by heating a single-mode optical fiber using hydrogen torch while elongating the fiber. The typical diameter of waist is 1–2 μm. The tapered fiber is placed in contact with the microbubble to avoid couple distance affecting. Although the contact may increase the mechanical modes damping and reduce the mechanical Q factors, this effect is very small. The circulation of light energy to and from microbubble couples back to the tapered fiber. Then, it travels to an optical powermeter module (Keysight 81636B) and a photodetector (Thorlabs PDB450C) through a 1 × 2 optical switch. The photodetector is connected to an electrical spectrum analyzer (Agilent N9010A) to observe the oscillation frequency spectrum directly. It is worth to point that both the functions of an optical powermeter module and electrical spectrum analyzer with photodetector can be realized by connecting a single data acquisition card to a photodetector, such as National Instruments (NI) product number: PCI−5154 that has maximum sample rate of 2 Gs s⁻¹ for signal with frequency measure range upper limit 200 MHz. Since we only need to track the movement of lowest optomechanical oscillation frequency (≤10 MHz) during temperature-sensing experiment, a lower sample rate data acquisition card (such as ≈100 MSPs) can be used and the frequency can be calculated with Fourier transfer of time−domain data as future field sensing solution.

We measure the optical WGM transmission spectrum of microbubble with temperature being controlled at 26 °C and determine the optical wavelength of pump light through the analysis of the deepest dip (red point in Figure 2b). Figure 2c shows excited breathing mode when the power of pump light is set as 5 mW, as showed in pervious works. The fundamental frequency component is the mechanical eigenfrequency of breathing mode. The high-order harmonic frequency components are related to phase modulation of breathing mode on multiple circulating pump light in microbubble.

Figure 2. Optomechanical oscillation temperature-sensing system setup. a) Schematic diagram of the temperature-sensing system. Inset: a microscopic picture of the silica hollow microbubble used in the double clamped sensor. b) Spectra of optical whispering gallery mode (WGM) resonance in the microbubble at 26 °C. c) Measured electric spectrum signals of breathing mode, center frequency is 9.61 MHz.
2.3. Temperature Measurement

We first investigate the effect of internal pressure variation $\Delta P_m$, radius variation $\Delta R$, and Young's modulus variation $\Delta E_{si}$ by fixing only one end of microbubble on copper sheet base, which avoid the effect of $\Delta F$. A fabricated microbubble with 100.3 $\mu$m radius and 2 $\mu$m wall thickness is used to construct the temperature sensor #1 ($L = 6$ cm, distance from UV glue to the other end of microcapillary). The mechanical-mode frequency is 10.535 MHz at 26 $^\circ$C. The electrical spectrum analyzer measurement range is set as 10.525–10.550 MHz, and the resolution bandwidth (RBW) is 50 Hz. Temperature rises from 26 to 26.7 $^\circ$C with step 0.1 $^\circ$C, and each measurement is carried out after 1 min temperature stabilizing. Figure 3a shows an obviously frequency shift of mechanical mode, and Figure 3b shows a good linear response with a temperature sensitivity of 2700 Hz $^\circ$C. The actual pressure change may be smaller than theoretically calculated, which avoid the effect of radius variation $\Delta R$.

We use the same method to excite the optomechanical oscillation and use its frequency spectrum for temperature-sensing experiments. A representative mechanical-mode frequency is 9.774 MHz at 26 $^\circ$C, as shown in Figure 5a. The electrical spectrum analyzer measurement range is set as 9.75–9.80 MHz, and the RBW is 50 Hz. Temperature rises from 26 to 26.6 $^\circ$C with step 0.1 $^\circ$C, and each measurement is carried out after 1 min temperature stabilizing. The black points in Figure 5a are original measurement data, the red lines are fitted data. It can be found that the mechanical-mode frequency increases significantly (marked by blue line). Figure 5b shows a good linear response between the mechanical oscillation frequency shift and the temperature change. The measurement temperature sensitivity is 11 300 Hz $^\circ$C. This is four times higher than the previous sensitivity 2700 Hz $^\circ$C and demonstrates that the sensitivity can be improved by $\Delta F$ effect. Using the same silica material parameters, the theoretical frequency $f_0$ will be 9.7765 MHz when $n$ is 15 according to Equation (I), which is close to measurement mechanical-mode frequency 9.774 MHz. $\Delta P_m = 3846.15$ Pa $^\circ$C$^{-1}$ is the same as sensor #1. Using the cross-sectional area of copper sheet $A_{cu} = 8.2 \times 1$ mm, the axial force effect is $\Delta F = 0.0013$ N. In the case of four effects, the theoretical temperature sensitivity $S_{T2} = 10$ 494 Hz$^\circ$C. The difference between theoretical and experimental sensitivity may be caused by the copper thermal expansion coefficient. The theoretical calculation uses the thermal expansion coefficient of pure copper. However, the experimental copper sheet contains alloy composition, so the actual thermal expansion coefficient is large. If we use the value 18.6 ppm$^\circ$C near brass coefficient, the theoretical temperature sensitivity is 11 335 Hz$^\circ$C.

Figure 3. The temperature response of single-ended sensor #1. a) Mechanical oscillation frequency shifts as a function of the surrounding temperature, from 26.1 to 26.7 $^\circ$C, 0.1 $^\circ$C step. b) Measurement temperature sensitivity, resulted from the linear fitting processing of 26.1–26.7 $^\circ$C data. The lines other than linear fitting represent the theoretical temperature sensitivity of each effect and the total theoretical temperature sensitivity $S_{T1}$. c) Heating and cooling experiments, the temperature range is 26.1–26.7 $^\circ$C, 0.1 $^\circ$C step.
Under an optomechanical oscillation mode with full width at half maximum (FWHM) of 114 Hz (see Figure 5c), we can easily locate the peak of optomechanical oscillation in frequency spectrum to $\Delta \nu_{\text{min}} = \text{FWHM}/100$, corresponding to the spectral resolution of our system, which is about 1.1 Hz. Estimated the resolution $\Delta T_{\text{reso}}$ of temperature sensor #2 to be $1 \times 10^{-4} \, ^\circ \text{C}$ accordingly ($\Delta T_{\text{reso}} = \Delta \nu_{\text{min}} / S_t$, $S_t$ is temperature sensitivity of sensor). Through the combination of optical WGM spectral direct demodulation and optomechanical oscillation frequency demodulation in same microbubble, we can extend the sensing temperature range while keeping high-temperature resolution. The two-stage method of optical

Figure 4. The WGM optical spectral shifts with temperature change. a) WGM transmission spectrum of single-ended microbubble in sensor #2 from 27 to 30.5 °C. With the increase of temperature, the spectrum experiences a redshift. b) WGM transmission spectrum of both-ended microbubble in sensor #2 from 28 to 31 °C, with the increase of temperature, the spectrum experiences a blueshift.

Figure 5. The temperature response of both-ended sensor #2. a) The both-ended mechanical oscillation frequency shifts as a function of the surrounding temperature, from 26.0 to 26.6 °C, 0.1 °C step. b) The measurement temperature sensitivity is indicated by the red line. The lines other than linear fitting represent the theoretical temperature sensitivity of each effect and the total theoretical temperature sensitivity $S_{T2}$. c) In above threshold behavior, linewidth 114 Hz was measured. FWHM, full width at half maximum.
scanning first and then precise excitation of optomechanical oscillation can integrate temperature sensors with large dynamic range and ultrahigh resolution.

Table 1 summarizes resolution comparison of WGM-based temperature sensors. Compared to similar devices simply observing the WGM optical spectrum, our sensor provides the best temperature resolution level. Only the polydimethylsiloxane (PDMS)-microcavities\([19,20]\) show the same order temperature resolution with our devices. However, PDMS materials have high optical loss regions in the 1100–2500 nm spectral.\([30]\) The increase of optical loss will reduce the Q value, thereby reducing the resolution. Especially in the most commonly used glass (1.05 W m\(^{-1}\) K\(^{-1}\)) and the radiator (0.18 W m\(^{-1}\) K\(^{-1}\)) of the PDMS sensor is lower than that of glass (1.05 W m\(^{-1}\) K\(^{-1}\)), which may slow response for applications with rapid temperature variation.

### 3. Conclusion

In conclusion, we have experimentally demonstrated and characterized the first, to our knowledge, radiation-pressure-driven optomechanical oscillation microresonator used in temperature sensing. The addition of optomechanical oscillation makes these sensors much higher resolution to temperature changes than traditional WGM spectrum shift method, and the microbubble does not require common methods such as liquid injection, coated, etc. Observed thermal sensitivity is 11 300 Hz °C\(^{-1}\) and ultrahigh-temperature resolution is 1 × 10\(^{-4}\) °C. Combined with optical WGM, we provide a new approach to large dynamic range, accurate temperature sensing. Finally, we also present a unique and exciting opportunity to continuous tuning of the discrete optomechanical oscillation frequencies.

### 4. Experimental Section

**Sensor Fabrication:** Wall-thickness-controlled microbubbles were fabricated by stretching and pressurizing microcapillaries in a high-temperature molten state.\([53]\) The fabricating system consisted of three parts, the fused tapering devices, the pressure control devices, and the hydrogen generator. The fabricating process was divided into two steps. First, the original microcapillary was drawn when heated by oxyhydrogen flame with a centimeter scale diameter. Second, we used oxyhydrogen flame with a millimeter scale diameter to heat the waist and a syringe was used to precisely inject air into the capillary, which made the waist swell and develop into a microbubble. During the swelling process, the diameter and the wall thickness could be controlled by adjusting the volume of injected air.

**Characterization of the Radius Effect:** When temperature rises, the WGM resonance wavelength shift of microbubble is described as\([18,14]\)

\[
\frac{\Delta \lambda}{T} = \left( \frac{\kappa}{n} + \alpha \right) \cdot \Delta T
\]

where \(\kappa = \Delta n/\Delta T\) is the thermo-optical coefficient and \(\alpha = (1/R) \cdot (\Delta R/\Delta T)\) is the deformation coefficient; \(n\) and \(R\) are the refractive index and the radius of the microbubble, respectively; and \(\lambda\) is the WGM resonance wavelength. For optical WGM spectrum, the difference between single- and both-ended fixations was whether the copper sheet thermal expansion would affect the microbubble deformation, namely the deformation coefficient \(\alpha\). In this case, the single- and both-ended wavelength shift equations are

\[
\frac{\Delta \lambda_s}{\Delta T} = \left( \frac{\kappa}{n} + \alpha_s \right) \cdot \Delta T
\]

\[
\frac{\Delta \lambda_b}{\Delta T} = \left( \frac{\kappa}{n} + \alpha_b \right) \cdot \Delta T
\]

where \(\alpha_s = \alpha_b = 0.5 \text{ ppm °C}^{-1}\). When we measure the \(\Delta \lambda\) and \(\dot{\lambda}\), the both-ended deformation coefficient is

\[
\alpha_b = \alpha_s - \left( \frac{\Delta \lambda_s}{\Delta T} - \frac{\Delta \lambda_b}{\Delta T} \right) \cdot \Delta T
\]

the radius variation effect (ppm °C\(^{-1}\)) into the cavity is therefore \(\Delta R = R \times \alpha_b\).

**Characterization of the Axial Force Effect:** The axial force \(\Delta F\) had the opposite effect on copper sheet and cylindrical shell model. However, the deformations of the two are equal and can be written as

\[
\Delta l_{cu} = \alpha_{cu} \Delta T - \frac{\Delta F}{A_{cu}E_{cu}}
\]

\[
\Delta l_{si} = \alpha_{si} \Delta T + \frac{\Delta F}{A_{si}E_{si}}
\]

where \(\Delta l_{cu/\text{si}}\) is the deformation of copper sheet/microtube, \(\Delta l_{cu} = \Delta l_{si}\); \(\alpha_{cu/\text{si}}\) is the thermal expansion coefficient; and \(A_{cu/\text{si}}\) is the cross-sectional area of copper microtube/microbubble.

### Table 1. Resolution comparison of WGM temperature sensors.

| Material                  | Microcavity type | Mechanism                        | Resolution °C |
|--------------------------|------------------|----------------------------------|---------------|
| Solid                    | Silica microbubble | WGM + opto-mechanical oscillation | 1 × 10\(^{-4}\) |
| Solid                    | Silica microbubble | WGM                              | 1 × 10\(^{-3}\) |
| Solid                    | PDMS microbubble  | WGM                              | 2 × 10\(^{-4}\) |
| Solid                    | Lithium niobate microdisk | WGM | 8 × 10\(^{-2}\) |
| Solid                    | Polymethylmethacrylate microbubble | WGM | 5 × 10\(^{-2}\) |
| Liquid                   | Liquid crystal microdroplet | WGM | 7.5 × 10\(^{-2}\) |
| Hybrid                   | Dye-doped microparticle | WGM + active lasing             | 2.7           |
| Hybrid                   | PDMS-coated silica microring | WGM | 1 × 10\(^{-4}\) |
| Hybrid                   | Liquid-filled silica microbubble | WGM | 8.5 × 10\(^{-3}\) |
|                         |                  |                                  | 1.75 × 10\(^{-3}\) |
area of copper sheet/microtube (shown in Figure 1a). $E_u = 120 \text{ GPa}, \alpha_u = 16.5 \text{ ppm} \text{ °C}^{-1}$. The axial force variation can be written as

$$\Delta F = \frac{(E_u - \alpha_u) \Delta T}{x_1 \ell_1 + x_2 \ell_2} \tag{9}$$

Acknowledgements

All authors commented on the manuscript. This work was supported by National Natural Science Foundation of China (Grant nos. 61735011 and 61675152); National Instrumentation Program of China (Grant no. 2013YQ030915); and the open project of Key Laboratory of Opto-Electronics Information Technology (Grant no. 2019KFKT007).

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

fiber sensing, microcavity, opto-mechanical oscillation

Received: February 27, 2022

Revised: March 30, 2022

Published online: April 26, 2022

[1] L. Caesar, S. Rahmstorf, A. Robinson, G. Feulner, V. Saba, Nature 2018, 556, 191.

[2] S. C. Riser, H. J. Freeland, D. Roemmich, S. Wijffels, A. Troisi, M. Belbeoch, D. Gilbert, J. Xu, S. Pouliquen, A. Thresher, P.-Y. Le Traon, G. Maze, B. Klein, M. Ravichandran, F. Grant, P.-M. Poulain, T. Suga, B. Lim, A. Sterl, P. Sutton, K.-A. Mork, P. J. Vélez-Belchi, I. Ansorge, B. King, J. Turton, M. Baringer, S. R. Jayne, Nat. Clim. Change 2016, 6, 145.

[3] P. M. Fulton, E. E. Brodsky, Y. Kano, J. Mori, F. Chester, T. Ishikawa, R. N. Harris, W. Lin, N. Eguchi, S. Toczko, T. Expedition, K. R. Scientists, Science 2013, 342, 1214.

[4] Y. Kano, J. Mori, R. Fujio, H. Ito, T. Yanagidani, S. Nakao, K.-F. Ma, Geophys. Res. Lett. 2006, 33, L14306.

[5] W. Liu, C. Specialist, B. Yang, Sens. Rev. 2007, 27, 298.

[6] C. M. Blanca, V. J. Cermin, V. M. Sastine, C. Saloma, Appl. Phys. Lett. 2005, 87, 202501.

[7] K. Toutouzas, M. Drakopoulos, J. Mitropoulos, E. Tsiamis, S. Vaina, M. Vavuranakis, V. Markou, E. Bosnakou, C. Stefanadis, J. Am. Coll. Cardiol. 2006, 47, 301.

[8] S. Kiyonaka, T. Kajimoto, R. Sakaguchi, D. Shimm, M. Omatsu-Kanbe, H. Matsuura, H. Imamura, T. Yoshikazi, I. Hamachi, T. Mori, Y. Mori, Nat. Methods 2013, 10, 1232.

[9] X. Zhu, J. Li, X. Qiu, Y. Liu, W. Feng, F. Li, Nat. Commun. 2018, 9, 2176.

[10] P. Lee, R. Bova, L. Schofield, W. Bryant, W. Dieckmann, A. Slattery, M. A. Govendir, L. Emmett, J. R. Greenfield, Cell Metab. 2016, 23, 602.
[48] T. Carmon, K. J. Vahala, Phys. Rev. Lett. 2007, 98, 167203.
[49] F. Vollmer, S. Arnold, Nat. Methods 2008, 5, 591.
[50] D. K. Cai, A. Neyer, R. Kuckuk, H. M. Heise, Opt. Mater. 2008, 30, 1157.
[51] D. K. Cai, A. Neyer, R. Kuckuk, H. M. Heise, J. Mol. Struct. 2010, 976, 274.
[52] R. Luo, H. Jiang, H. Liang, Y. Chen, Q. Lin, Opt. Lett. 2017, 42, 1281.
[53] J. F. Jiang, Y. Z. Liu, K. Liu, S. Wang, Z. Ma, Y. N. Zhang, P. P. Niu, L. Shen, T. G. Liu, Appl. Opt. 2020, 59, 5052.
[54] Z. Liu, L. Liu, Z. Zhu, Y. Zhang, Y. Wei, X. Zhang, E. Zhao, Y. Zhang, J. Yang, L. Yuan, Opt. Lett. 2016, 41, 4649.
[55] J. R. Berger, E. S. Drexler, D. T. Read, Exp. Mech. 1998, 38, 167.