Progress of optomechanical micro/nano sensors: a review

Xinmiao Liu\textsuperscript{a,b,c}, Weixin Liu\textsuperscript{a,c,*}, Zhihao Ren\textsuperscript{a,c,*}, Yiming Ma\textsuperscript{a,c,d}, Bowei Dong\textsuperscript{a,c}, Guangya Zhou\textsuperscript{b,c}, and Chengkuo Lee\textsuperscript{a,c,d,e}

\textsuperscript{a}Department of Electrical and Computer Engineering, National University of Singapore, Singapore, Singapore; \textsuperscript{b}Department of Mechanical Engineering, National University of Singapore, Singapore, Singapore; \textsuperscript{c}Center for Intelligent Sensors and MEMS (CISM), National University of Singapore, Singapore, Singapore; \textsuperscript{d}National University of Singapore Suzhou Research Institute (NUSRI), Suzhou, China; \textsuperscript{e}NUS Graduate School for Integrative Science and Engineering, National University of Singapore, Singapore, Singapore

\textbf{ABSTRACT}

Optomechanical sensing based on the coupling between mechanical motions and optical resonances has attracted huge interest in sensor applications due to its small footprint, high sensitivity, low detection limit, and electromagnetic immunity. Optomechanical sensors that detect from mechanical motion at \textit{um} scale to molecular vibration at \textit{nm} scale have found various applications such as force, inertia, acoustic, chemical, and thermal sensing, etc. In this review, we provide an overview of the recent progress of optomechanical sensors. Three development fields of optomechanical sensors are reviewed, which are passive optomechanical sensors, electro-optomechanical sensing platforms, and molecular vibration sensing schemes. The sensor configurations, applications, and integrations are described. In the end, we also provide our perspectives on the future development directions of optomechanical sensors.

\textbf{KEYWORDS}

Optomechanical sensors; physical sensing; chemical sensing; molecular vibration; photothermal effect

1. Introduction

Starting from the late twentieth century, micro-electro-mechanical systems (MEMS) had become an enabling technology that provided many opportunities in the integration with micro-optics. Termed as micro-opto-electro-mechanical systems (MOEMS), this new class of microsystems mainly focus on the demonstration of the miniaturized optical components at its early stage.\textsuperscript{[1,2]}

During this period, the advances in telecommunication and fiber-optics technology enabled the development of many MOEMS components, including variable optical attenuators (VOA) for optical signal power levelling,\textsuperscript{[3–9]} optical switches for optical matrix connection in data centers,\textsuperscript{[10–15]} tuneable lasers for wavelength conversion,\textsuperscript{[16–19]} etc. Moving forward, MOEMS technologies also find applications in many other thriving fields. For example, the MOEMS scanners are promising for miniaturized LiDAR and display applications;\textsuperscript{[20,21]} the tuneable optical spectrometers show possibilities for the portable spectral analysis.\textsuperscript{[22]} More recently, on-chip optomechanical systems have been widely explored for applications in quantum communication.\textsuperscript{[23,24]}
parallel to demonstrating MOEMS components in the applications in the telecommunication field, many efforts have also been made to explore their sensing capability.

In recent years, with the ever-increasing demand for advanced sensing technologies that enable Internet-of-Things (IoT) applications in homeland securities, environmental monitoring, industrial process control, personal healthcare, etc., high precision and sensitive sensors that could form smart sensor networks are being developed.\(^{25-29}\) Each sensor node consisting of different types of sensors that detect multiple external stimuli such as temperature change, acceleration, rotation, sound, radiation, etc., puts up challenges but also gains much attention in research. In general, there are two major readout schemes for sensor signals, which are electrical and optical output.\(^{30}\) Resistive sensors that measure resistance change as output signals are widely used for pressure and thermal sensing,\(^{31-34}\) capacitive sensors that measure capacitance differences as output signals are broadly used for acoustic and inertia sensing,\(^{35-37}\) piezoelectric sensors that measure the generated voltage as output signals are also commonly used for force and acoustic sensing but with the much lower power required.\(^{38-42}\) Optical sensors that measure the optical intensity change or resonance wavelength shift are targeted at much higher precision sensing due to their high resolution and sensitivity.\(^{43}\) Compared to conventional optical sensors that rely on

---

### Nomenclature

| Symbol | Description                       | Symbol | Description                       |
|--------|-----------------------------------|--------|-----------------------------------|
| \(K_b\) | Boltzmann constant                | \(FBG\) | Fiber Bragg gratings              |
| \(T\)  | Temperature                        | \(LiNbO_3\) | Lithium Niobate                   |
| \(Q\)  | Quality factor                     | \(AIN\) | Aluminum Nitride                  |
| \(m_{eff}\) | Effective mass                   | \(IR\)  | Infrared                          |
| \(k_{eff}\) | Spring constant                   | \(FTIR\) | Fourier transform infrared        |
| \(\mu m\) | Micrometer                        | \(SEIRA\) | Surface-enhanced infrared absorption |
| \(Hz\)  | Hertz                             | \(MIM\)  | Metal-isolator-metal              |
| \(\omega\) | Resonance frequency               | \(HN-SEIRA\) | Hybrid nanofluidic surface-enhanced infrared absorption |
| \(j\)   | Imaginary unit                    | \(TCMT\) | Temporal coupled-mode theory      |
| \(h\)   | Plank’s constant                  | \(EIT-like\) | Electromagnetic-induced-transparent-like |
| \(f\)   | Frequency                         | \(2D\)  | 2-dimensional                     |
| \(\lambda\) | Wavelength                       | \(CO_2\) | Carbon Dioxide                    |
| \(c\)   | Speed of light                    | \(NO_x\) | Nitrogen Oxides                   |
| MEMS    | Micro-electro-mechanical systems  | \(SO_2\) | Sulfur dioxide                    |
| MOEMS   | Micro-opto-electro-mechanical systems | \(CH_4\) | Methane                           |
| VOA     | Variable optical attenuators      | \(VOCs\) | Volatile organic compounds        |
| LiDAR   | Light Detection and Ranging       | \(NDIR\) | Non-dispersive infrared           |
| RF      | Radio frequency                   | \(PEI\)  | Polyethyleneimine                 |
| IoT     | Internet-of-things                | \(CMOS\) | Complementary metal-oxide-
| Si      | Silicon                           |         | semiconductor                     |
| SiO_2   | Silicon Dioxide                   | \(N_2\)  | Nitrogen                          |
| NRR     | Nano-ring resonator               | \(MoS_2\) | Moly-disulfide                    |
| AFM     | Atomic Force Spectroscopy         | \(MOF\)  | Metal-organic framework           |
| MIR     | Mid-infrared                      | \(LED\)  | Light-emitting diode              |
| SNR     | Signal-to-noise ratio             | \(RI\)   | Refractive Index                  |
| PhC     | Photonic Crystal                  | \(TEC\)  | Thermal expansion coefficient     |
| PDMS    | Polydimethylsiloxane              | \(BSTP\) | Bond-selective transient phase    |
| SiN     | Silicon Nitride                   | \(PPT\)  | Plasmonic photothermal            |
| WGM     | Whisper Gallery Mode              | \(LSPR\) | Localized surface plasmon resonance |
| MZI     | Mach-Zehnder interferometer       |         |                                   |
| FOM     | Figure-of-merit                   | \(SARS-CoV-2\) | Severe acute respiratory syndrome coronavirus 2 |
| TE      | Transverse electric               | \(WPS\)  | Widefield photothermal sensing    |
| TM      | Transverse magnetic               | \(BSTP\) | Bond-selective transient phase    |
| SAW     | Surface acoustic wave             | \(CNT\)  | Carbon nanotube                   |
| MRI     | Magnetic resonance imaging        |         |                                   |

---
direct light-matter interaction, optomechanical sensors, which firstly convert external stimuli to mechanical motions that further interact with optical modes, are not only naturally suitable for physical sensing applications but also provide additional advantages such as higher sensitivity and smaller footprint due to the stronger perturbation to the optical modes by optomechanical effects.

The mechanisms for optomechanical sensing can be contributed by various effects, e.g., the mechanical movement-induced optical path length change and evanescent field coupling change, the photoelastic and moving interfaces induced microscopic photon-phonon coupling. Based on these phenomena, different configurations of optomechanical sensors are developed, including photonic crystal waveguides on cantilevers, freestanding microdisk cavities, and Fabry-Perot cavities, etc. Currently, in the broader terms of optomechanical sensing, we see three major fields of development, as shown in Figure 1. The firstly developed field features passive optical resonators placed on or close to mechanical structures, which are used to perceive external stimuli. The vibration of the mechanical structures, usually suspended in the form of cantilever beams or disks, will be optomechanically coupled into optical modes in the resonators, results in a wavelength shift of output signal. The second field appears in recent years where internal excitations are placed, normally through electrical modulations in the radio frequency (RF) range. The electrical resonance coupled with external mechanical input will add tunability and provide more degrees of freedom for the improvement of sensitivity. The third field focuses on molecular level vibration detection. A molecular vibration is a periodic motion of contained atoms relative to each other and can be described using classical mechanics. Therefore, the sensors that optically detect molecular vibrations are regarded as a type of optomechanical sensors as well in this review. Molecules absorb light at their vibration frequencies. Thus, these sensors based on absorption spectroscopy provide intrinsic selectivity.

In this review, we focus on the development of micro/nano optomechanical sensors and their applications. The structure of this review is as follows. Section 2 introduces typical passive optomechanical sensor configurations and applications, including cantilever-based optomechanical...
Figure 2. Cantilever-based optomechanical sensors. (a)–(c) Cantilever-based optomechanical sensors with photonic crystal resonators as sensing elements.\textsuperscript{79–81} (d)–(g) Micro-cavity-based optomechanical sensors with micro/nano cantilever actuation.\textsuperscript{82–84}
sensors and some other configurations for physical sensing. Section 3 discusses the latest and potential optomechanical sensing platforms with electrical modulation in the RF regime, and sensing demonstrations are presented. Section 4 further explores optomechanical sensing on the molecular vibration level with both nanoantenna and photothermal assistance and reports on gas/liquid sensing applications. In the end, we summarize the optomechanical sensing development with a perspective on future development.

2. Passive optomechanical sensors

2.1. Cantilever-based optomechanical sensors

The earlier generation of optomechanical sensors generally relies on larger displacement to induce change that is more prominent in the optomechanical system for detection. One of the common designs is to use a micro-cantilever as a mechanical input structure to interact with the environment.[76,77] The advantages of using such a cantilever allow for larger mechanical deformation. The force sensitivity of the cantilever based optomechanical system is limited by thermal forces acting on the mechanical resonator,[78] with the spectral density derived using fluctuation-dissipation theorem:

\[ S = 4k_b T \frac{m_{\text{eff}} \Omega}{Q} = 4k_b T \frac{k_{\text{eff}}}{Q Q} \]  

(1)

where \( k_b \) is the Boltzmann constant, \( T \) is the bath temperature, and \( Q = \Omega/\Gamma \) is the mechanical quality factor, \( m_{\text{eff}} \) and \( k_{\text{eff}} \) are the effective mass and spring constant of the cantilever. Therefore, in order to suppress the thermal noise, both the spring constant of the device and effective masses need to be minimized. However, reducing the spring constant will lower the mechanical frequency and thus limit the time resolution, while reducing the effective masses will increase the mechanical frequencies. At the same time, smaller device dimensions will lessen the viscous damping which will reduces the mechanical \( Q \), and further reduce the thermal noise. In summary, by reducing the effective mass and dimensions, the sensitivity will be improved. The optical readout configuration can be either photonic crystal resonators or microdisk resonators, as illustrated in Figure 2. In 2009, Xiang and Lee proposed a nanophotonics-based micro-cantilever sensor aimed for chemical analysis,[79] as shown in Figure 2(a). The deformation of the photonic crystal located at the edge of the micro-cantilever will cause a resonant wavelength shift, therefore measuring the strain experienced by the micro-cantilever. A comparison of the micro-cantilever working in air and water, as well as the platform of Si/SiO\(_2\) and Si, was investigated, and the results suggested such device is more suitable for in-water measurement using silicon (Si)/silicon oxide (SiO\(_2\)) as a minimum detectable Z-displacement of 0.6 \( \mu \)m and strain of 0.0098% were obtained through simulation. Before that, C. Lee et al. have also done the fundamental study of such 2D photonic crystal integrated micro-cantilever sensor, showing a linear change of resonant wavelength shift against strain.[85] Mai et al. have further optimized the photonic crystal resonator-based micro-cantilever sensor for improved sensitivity,[80] as depicted in Figure 2(b). Two different layouts of hexagonal nano-ring resonators (NRR) were proposed in their study. B. Li et al. performed a configuration analysis on the photonic crystal based micro-cantilever sensors, as shown in Figure 2(c). It was found that the dual-ring resonator shape deformation and the separation of these nano-cavities on the micro-cantilever could contribute to a significant change in the sensing characteristics, the quality (Q) factor of 3000 and the minimum detectable force of 7.58 nN could be achieved.[81] He has also computationally characterized the hexagonal dual-nano-ring-based photonic crystal cantilever sensor in another work.[86] The photonic crystal based ring resonator sensors have been further investigated by B. Li et al. for different sensing applications.[87–91] Overall, the dimensions of photonic crystal based cantilever sensors reported are from 25 to 50 \( \mu \)m long and 15 \( \mu \)m wide, while the state-of-the-art capacitive and piezoelectric
based cantilever sensors are having the length in hundreds to thousands of μm.\textsuperscript{[92–97]} Another widely designed optomechanical sensing layout is through the interactions between a micro-disk resonator and a micro/nano-cantilever. Compared with previously mentioned structures where photonic crystals are integrated on top of a micro-cantilever, such configuration effectively reduces the footprint and increases the Q factor that allows a much higher detection limit.\textsuperscript{[98–100]} Compared with the first type of cantilever-based optomechanical sensor with photonic crystal readout, such configuration could effectively reduce the footprint by 90% (from 750 μm^2 to 78.5 μm^2) while increasing the quality factor by 18 times (from 5500 to 100,000).\textsuperscript{[80,82]} C. Doolin et al. have demonstrated multidimensional optomechanical cantilevers with only one end clamped as shown in Figure 2(d), thus providing extra sensitivity for both in-plane and out-of-plane motions.\textsuperscript{[83]} Different lengths of cantilevers from 2 to 8 μm were fabricated and characterized, and in terms of the trade-off in force-sensing ability, a large cantilever with lower spring constant excels in the vacuum environment while a shorter cantilever with higher stiffness provides better force sensing in ambient. Srinivasan et al. presented an ultra-compact cantilever-microdisk optomechanical system that is able to achieve a high Q factor ($Q \approx 10^5$), as shown in Figure 2(e).\textsuperscript{[82]} The monolithically integrated subpicogram silicon cantilever with a sharp probe tip is placed around a microdisk optical resonator with a nanoscale gap, so that any tiny vibrations that cause the mechanical modes of the cantilever will affect the optomechanical coupling between the cantilever and the microdisk resonator, resulting in a sharp RF amplitude change. At the same time, optically induced stiffening was also observed. The sensitive transduction of the motion could lead to precision AFM applications. Chae et al. also proposed a similar structure for chemical composition and thermal conductivity measurements,\textsuperscript{[71]} as shown in Figure 2(f). A subpicogram micro cantilever with a sharp probe tip is integrated with a photothermal induced resonance system, in which the mid-infrared (MIR) laser induced thermal expansion causes the cantilever to vibrate with its amplitude directly proportional to the sample's absorption. Such motion will be optomechanically coupled to the microdisk resonator and thus be capture by the resonance shift in the near-infrared regime. A 50-time enhancement of the signal-to-noise (SNR) ratio of this system is measured comparing with conventional AFM cantilever. Kim et al. designed a cavity optomechanical torque sensor with magnetic actuation and feedback cooling,\textsuperscript{[84]} as shown in Figure 2(g). An optical microdisk resonator is coupled with an arced torsional resonator similar to a cantilever, where a trilayer ferromagnetic needle is integrated at the middle for magnetic field sensing. The magnetic field in vertical direction will induce an in-plane torque, which can be measured by optomechanical coupling change.

To sum up, cantilever-based optomechanical sensors can be categorized into two main configurations: photonic crystal cavities built on the cantilever leveraging the shape deformation of the resonators, and optomechanical coupling between the cantilever and microcavities. These types of optomechanical sensors are mainly found in chemical sensing and AFM applications, where high precision measurements are needed. Table 1 below summarized the different cantilever-based optomechanical sensors' performance and sizes.

| Sensing unit          | Limit of detection | Resolution     | Q-factor | Device dimensions | Reference       |
|-----------------------|--------------------|----------------|----------|-------------------|-----------------|
| PhC                   | 0.26 μm            | 0.0132%        | N. A.    | 50 × 15 μm^2      | 2008,\textsuperscript{[85]} |
| PhC                   | 0.6/0.812 μm (air/water) | 0.0098%/0.0144% | N. A.   | 50 × 15 μm^2      | 2009,\textsuperscript{[79]} |
| PhC                   | 62.5 nN            | 0.0133%        | N. A.    | 50 × 15 μm^2      | 2009,\textsuperscript{[91]} |
| PhC                   | 75.7 nN            | 0.023%         | >5000    | N. A.             | 2011,\textsuperscript{[80]} |
| PhC                   | 7.58 nN            | N. A.          | >3000    | 50 × 15 μm^2      | 2011,\textsuperscript{[81]} |
| PhC                   | 37 Nn              | N. A.          | 3800     | 50 × 15 μm^2      | 2011,\textsuperscript{[86]} |
| Microdisk Resonator   | 5.1 × 10^{-5} nN   | 4.4 × 10^{-6} nm Hz^{-1/2} | 100,000  | 10 μm diameter    | 2011,\textsuperscript{[82]} |
| Microdisk Resonator   | 2 fm Hz^{-1/2}     | 130 aHz^{-1/2} | 3600–7800 | 20 μm diameter    | 2014,\textsuperscript{[83]} |
| Microdisk Resonator   | 25 fm Hz^{-1/2}    | 0.58 zNm Hz^{-1/2} | 53,000   | 8.8 μm diameter   | 2017,\textsuperscript{[84]} |
2.2. Other optomechanical sensor configurations and applications

Physical sensing using optomechanical sensors has attracted huge interest due to the high sensitivity and resolution. Through the conversion from physical stimuli, such as sound, acceleration, pressure, magnetic force, etc., into either static mechanical displacement or dynamic mechanical resonance shift, the corresponding optical coupling would pick up such infinitesimal variations and accurately reflected them in the output signal. Figure 3(a) shows a magnetic field sensor based on coupled photonic crystal nanobeam cavities reported by Du et al.\textsuperscript{[107]} The magnetic field-induced Lorentz force will cause the cavity nanobeam to move relative to the waveguide,
and thus changing the optical transmission. The resonance wavelength shift of a selected super-mode is used to calculate the field strength. Compared with Micro-Electro-Mechanical Systems (MEMS) based magnetometers,[101] the optomechanical-based magnetic field sensor has a much smaller footprint of only 70 µm by 40 µm, while achieving the sensitivity of 22.9 mV/T and resolution of 48.1 µT/Hz^{1/2}. S. Basiri-Esfahani et al. demonstrated ultrasound sensing with optomechanical microcavities, as shown in Figure 3(b).[108] A lithographically fabricated Si microdisk cavity with a thin tether to the substrate is used to optomechanically couple the acoustic wave with optical resonance. By measuring the power spectral density across the ultrasound range from 1 kHz to 1 MHz, the achieved noise equivalent pressure reaches 8–300 µPa Hz^{1/2}. Compared with traditional air-coupled or liquid-coupled ultrasound sensors, this work has two to three orders of improved sensitivity.[102,109,110] Figure 3(c) shows a nano-opto-mechanical pressure sensor based on ring resonators built on thin diaphragms, as reported by Zhao et al.[111] Due to the pressure-induced mechanical deformation of the ring resonators, there is a linear shift of the spectrum, which allows the detection of the pressure change. An array of such micro rings with different ring sizes and diaphragm thicknesses could be formed for various detection sensitivities. As a result, a peak sensitivity of 1.479 pm/kPa was detected with a resolution of 1.36 kPa. Figure 3(d) illustrates 1D photonic crystal strain sensors making of periodic nanorods embedded in deformable polydimethylsiloxane (PDMS) substrates, as reported by Lu et al.[103] Due to the planar strain variation, the photonic crystal exhibits a large wavelength response, and by placing the three periodic nanorods in arbitrary directions and comparing the wavelength shifts with the database, the strain sensors can precisely identify the direction, type, and value of the unknown planar strains. H. Xiong et al. have also proposed an optical sensor for electrical charges measurement based on optomechanically induced difference-sideband generation.[104] The detection is through the change of efficiency of upper and lower difference-sideband generation under different charges. Such a device could achieve few orders of magnitude better than linearized electrical charge sensors. As depicted in Figure 3(e), Liu et al. have presented a nano-optomechanical displacement sensor based on a nanomechanical, three-dimensional directional coupler with an integrated photodiode.[112] A small displacement imprecision of 45 fm-Hz^{1/2} and a large dynamic range of more than 50 dB are obtained. Due to the optical cavity-free design, an ultra-wide optical bandwidth of more than 80 nm has been achieved, reducing the need for tunable laser at the same time making it less frequency noise affected. Other than the conventional CMOS fabrication process, which most optomechanical sensors are made from, the recent advancement in 3D printing has also made it possible to fabricate ultracompact optomechanical sensors. Figure 3(f) shows an optomechanical microresonator-based acoustic sensor fabricated on top of a fiber-tip with μ-printing technology, as reported by Yao et al.[105] The 3D printed spiral-shaped microresonator has formed a Fabry-Perot cavity at the tip of a fiber, making the detection of acoustic wave possible. They have experimentally measured a high sensitivity level of 118.3 mV/Pa and a low noise equivalent acoustic signal level of 0.328 µPa/Hz^{1/2}. One thing to take note of is that owing to the spiral-shaped mechanical structure, the maximum sensitivity can be further enhanced by 40.1 times when the optomechanical resonator operates at its natural resonance.

Optomechanics has also become one of the most promising platforms for precise inertial sensing, such as accelerometers and gyroscopes. This can be mainly attributed to its possibility to detect the motion at or even below the standard quantum limit (SQL), thus making optomechanical transducers particularly suitable for weak incoherent inertial measurement. The optomechanical systems principally involve optomechanical cavities, in which radiation pressure coupling between optical and mechanical domains is greatly enhanced. As a result, the optical resonance frequency is exquisitely sensitive to mechanical motion. Furthermore, the optomechanical cavities enable an unprecedented reduction in the footprint of the sensors.

Optical detection of acceleration offers superior resolution and smaller footprint, compared with those realized using piezoelectric and capacitive, as shown in Table 2. Nevertheless, many of
Table 2. The summary of accelerometers.

| Operation method/type | Footprint of device ($\mu$m²) | Footprint of proof mass ($\mu$m²) | Resonance frequency | Sensitivity | Resolution | Limit of Detection | Bandwidth | Figure of Merit (FOM)# | Reference |
|-----------------------|-------------------------------|----------------------------------|---------------------|-------------|------------|--------------------|-----------|------------------------|-----------|
| Electrostatic         | 11,380 × 7550                 | 4500 × 4750                      | 734 Hz              | 2.39 V/g    | 50.3 µg/Hz$^{1/2}$ | 50 µg              | N. A.     | 0.07                   | 2012[113] |
| Electrostatic         | 2000 × 2000                   | 1500 × 1500                      | 4.255 kHz           | 100 fF/g    | 4 aF/Hz$^{1/2}$ | 10–100 mg           | 3–4 kHz   | 0.014                  | 2018[114] |
| Electrostatic         | 4200 × 2250                   | N. A.                            | 16.061 kHz          | 297.5 Hz/g  | 13.2 mg/Hz$^{1/2}$ | 13.2 mg             | N. A.     | 0.3                    | 2021[115] |
| Piezoelectric         | 5000 × 5000                   | 2400 × 2400                      | 1.279 kHz           | 9.1 mV/g    | N. A.       | N. A.               | N. A.     | 0.025                  | 2016[116] |
| Piezoelectric         | 2000 × 1600                   | 1000 × 1000                      | 140.7 kHz           | 28.4 Hz/g   | 14.1 mg/Hz$^{1/2}$ | 14.1 mg             | N. A.     | 0.38                   | 2017[117] |
| Piezoelectric         | 7000 × 7000                   | 2000 × 2000                      | 3.084 kHz           | 150 mV/g    | N. A.       | N. A.               | N. A.     | N. A.                  | 2019[118] |
| Optomechanical        | N. A.                         | 150 × 60                         | 27.5 kHz            | 100 mV/g    | 10 µg/Hz$^{1/2}$ | 10 µg              | 5–25 kHz | 0.256                  | 2012[70]  |
| Optomechanical        | 200 × 700                     | 20 × 40                          | 103 kHz             | 22 pm/g     | N. A.       | N. A.               | 30 kHz    | 0.185                  | 2013[19]  |
| Optomechanical        | 10,600 × 15,000               | N. A.                            | 10.7 kHz            | N. A.       | 3 mg/Hz$^{1/2}$ | 3 mg               | 1.5–12 kHz| N. A.                  | 2014[120] |
| Optomechanical        | 200 × 160                     | 120 × 150                        | 71.3 kHz            | 1600 Hz/g   | 8.2 µg/Hz$^{1/2}$ | 50.9 µg             | 100 Hz    | 2.29                   | 2020[121] |

FOM for resonant-based accelerometers is calculated as $\Delta f/f$, where $\Delta f$ is the shifted frequency under 1 g acceleration, $f$ is the resonant frequency. FOM for non-resonant-based accelerometers is calculated as $\Delta V/V$ or $\Delta C/C$, where $\Delta V$($\Delta C$) is the changed voltage (capacitance) under 1 g acceleration, $V$($C$) is the initial voltage (capacitance).
these optical accelerometers still rely on relatively bulky mass and fail to enable chip-scale integration. Fortunately, we can design sensitive on-chip optomechanical accelerometers by leveraging the displacement readout of optomechanical cavities. In 2012, A. G. Krause et al. proposed the first ultrasensitive on-chip optomechanical accelerometer. The structure is shown in Figure 4(a). In their work, an integrated silicon nitride (SiN) zipper photonic-crystal optomechanical cavity is utilized. The cavity consists of two patterned photonic-crystal nanobeams, with one attached to a movable test mass structure held by nano-tethers and the other fixed to the bulk. The optical resonance frequency is susceptible to test mass motion due to the well-confined optical cavity field between two nanobeams. The achieved acceleration resolution is on the order of a few \( \mu \text{g-Hz}^{-1/2} \) with a bandwidth above 25 kHz, shows an extraordinary performance compared with its competitors. Afterward, several kinds of optomechanical accelerometers were proposed. In 2012, D. N. Hutchison et al. demonstrated a z-axis accelerometer using two stacked rings (one fixed and one suspended above it) formed resonance cavity, having a sensitivity of 22 percent-per-g optical modulations with this high optical Q factor devices. In 2013, Cervantes demonstrated a self-calibrating optomechanical accelerometer with a monolithic fused-silica mechanical oscillator with the integrated fiber micro-cavity. This device is capable of reaching nano-g-Hz \(^{-1/2} \) sensitivity over a bandwidth of several kHz. At the same time, B. Dong et al. demonstrated a novel in-plane accelerometer with Whisper Gallery Mode (WGM) ring resonator employed, and the strong optomechanical interactions allow the detection sensitivity of around 3.3 pm/g at low-power operation. Moreover, in 2016, a ring-resonator-coupled Mach-Zehnder interferometer (MZI) based waveguide accelerometer is proposed. And the sensitivity boosted to 111.75 mW/g, with a 393-fold increase compared with a conventional MZI accelerometer.
In general, these motion sensors should not only allow for these kinds of accelerometers but also displacement-based rotation sensors. In 2016, Li et al. applied the optomechanical mechanism to measure the angular momentum of light and the optical torque. The optical image of the device and the schematic measure setup are shown in Figure 4(b). The authors first separated the transverse electric (TE) and transverse magnetic (TM) modes of light, injected them into the suspended Si waveguide with strong birefringence, and then independently controlled the phase and power of light before combined by a Y junction. The relative phase $\varphi$ of light can be accurately controlled through modulation of TE and TM modes separately, thus producing different optical torque in the optomechanical interaction section. A nanobeam embedded with two one-dimensional photonic crystal nanocavities is attached to the waveguide. It provides sensitive detection of the optical torque, which can be read out by the coupling waveguide. The exploration of angular momentum exchange between photons and devices in the integrated photonic platform in this work is ubiquitous. It has an exciting potentiality to design torsional optomechanical sensors, such as gyroscopes and torsional magnetometry. In 2016, Kilic reported an optomechanical vibratory gyroscope, as depicted in Figure 4(c), achieving a noise-equivalent rotation rate of $3^\circ$/h Hz$^{-1/2}$ under atmospheric-pressure conditions. The gyroscope consists of the torsional 2D scanner with its rotation axis parallel to the silica post. The gold-coated optical fibers from Fabry-Perot interferometers with the reflective surface of the scanner to measure torsional displacement. The fibers can be repositioned to probe the calibration points to measure the frequency response and noise of the torsional displacement in the two axes. The theoretical bandwidth of the proposed gyroscope can reach 200 Hz, although it is sensitive to thermal effects, and extra packaging and temperature stabilization techniques should be implemented. Different kinds of gyroscopes are summarized in Table 3.

The exquisite motion sensitivity also enables optomechanics as a prominent candidate of other motion-based sensors such as mass spectrometers and pressure sensors. In 2019, M. Sansa et al. proposed a compact and precise nano-optomechanical resonator for single-particle mass analysis. As shown in Figure 4(d), an electrostatic-actuated nanoresonator is laterally coupled to the optical cavity. The motion of the nanoresonator detunes the optical cavity and modulates the output optical power at the mechanical frequency, which is sensitive to the loaded mass change. This device performed mass spectrometry ranging from 2.8 to 7.7 MDa in less than 5 min and demonstrated excellent stability.

### Table 3. The summary of gyroscopes.

| Operation method/type | Footprint of devices ($\mu$m$^2$) | Device performance | Bias stability | Resolution | Reference |
|-----------------------|------------------------------------|--------------------|---------------|------------|-----------|
| Electrostatic gyroscope | $5.130 \times 4.090$ | Q-factor: 75 | N. A. | $2 \times 10^-7$/s | 2012, [137] |
| Electrostatic disk resonator | $6.00 \times 6.00$ | Q-factor: 50,000 | $3.29 \times 10^-7$/h | $>3.29 \times 10^-7$/h | 2013, [132] |
| Piezoelectric SAW resonator | $1.200 \times 7.500$ | Q-factor: 150 | N. A. | $172 \times 10^-7$/s | 2011, [133] |
| Piezoelectric SAW resonator | $7.850 \times 7.850$ | Q-factor: 945 | N. A. | $1000 \times 10^-7$/h | 2018, [134] |
| Optomechanical ring resonator | $6.25 \times 10^6$ | Q-factor: $3 \times 10^6$ | $0.1 \times 10^-7$/s | $400 \times 10^-7$/h | 2017, [135] |
| Optomechanical ring resonator array | $5.00 \times 4.00$ | Q-factor: $5 \times 10^5$ | N. A. | $0.05 \times 10^-7$/h | 2013, [136] |
| Optomechanical ring resonator | $7.0 \times 7.0$ | Q-factor: $3.7 \times 10^5$ | N. A. | $2 \times 10^-7$/s | 2014, [137] |

### 3. Electro-optomechanical sensing platforms

#### 3.1. Acousto-optical sensing platforms

While optomechanical cavities, as discussed in the previous section, provide access for signal transduction between the optical and mechanical domains. It is also of interest to combine the optomechanical cavity systems with the radiofrequency domain. This combination provides active tuning methods of the cavity and more degrees of freedom to enhance the sensitivity.
Electrostatic-driven and piezoelectric-driven are two mainstream approaches to probe and detune the optomechanical cavity and provide the bridge for energy exchange between phonon and photon.\cite{144} This interaction between coherent stimulated acoustic phonons and light beams, known as acousto-optical interaction, offers excellent possibilities for a new class of inertial sensing without movable structure, thus enhancing both the reliability and the tuning frequency.

Typically, existing MEMS-based inertial sensors need a large released mass, making the sensors vulnerable to shock.\cite{145,146} Acousto-optic sensing shows its potential to address this issue. As depicted in Figure 5(a), an acousto-optic gyroscope consisting of two inherently matched piezoelectric surface acoustic wave resonators and a photonic MZI structure is proposed by M. Mahmoud in 2018.\cite{147} Here, surface acoustic wave (SAW) resonators enable the realization of a large unreleased mass and wide bandwidth operation. The rotational information is acquired from the induced Coriolis force $F_c$ by checkerboard shaped metallic pillars, which is expressed as:

$$F_c = -2M_p \Omega_z \times v_p$$ \hspace{1cm}(2)$$

Where $M_p$ is the effective mass of the moving pillars, $\Omega_z$ is the out-plane rotation, $v_p$ is the longitudinal vibration velocity. This Coriolis force is then mapped to a change in the

Figure 5. Acousto-optic sensing platform. (a) Acousto-optical gyroscope.\cite{147} (b) Optomechanical mass sensor.\cite{124} (c) Electro-optomechanical particle sensor.\cite{148} (d) FBG based acousto-optic sensors for MRI applications.\cite{149}
effective index of the optical waveguide through the acousto-optic effect, which is read by a push-pull MZI structure. This AO gyroscope shows a sensitivity of 48 nV/(°/s) and the angular random walk of 60°/h^{1/2}. Low-dimensional materials, such as graphene, semiconducting nanowires, and carbon nanotubes, featuring numerous unique properties and deployed widely,[150–153] are also employed in optomechanical sensing for further reduction inertial mass of the mechanical resonators. These strategies offer many opportunities for high-precision force and mass sensing. Nevertheless, the sensitivity is often limited by measurement imprecision and thermo-mechanical noise. In 2016, Weber studied the force sensitivity of multilayer graphene mechanical resonators coupled to superconducting cavities.[124] As shown in Figure 5(b), the graphene flake is clamped between poly topping (methyl metracylate) and niobium support electrodes. This graphene mechanical resonator is coupled to the superconducting LC cavity through the capacitance, between which a constant voltage controls the separation. In their work, the best force sensitivity in this device is \( (s_F)^{1/2} = 390 \pm 30 \text{ zN Hz}^{1/2} \), by operating at low pump photon condition of \( 4 \times 10^5 \) and the careful design of improved thermal anchoring. While the force sensitivity is primarily limited by the measurement imprecision and frequency noise at low pump power, and by optomechanical damping and Joule heating at high pump power. Apart from inertial sensing, the optomechanical resonator can also be employed in fluid media for particle sensing or liquid sensing.[154–158] In 2017, Suh et al. demonstrated precise particle sensing in microfluidics, achieved by the long-range optomechanical interaction.[148] As shown in Figure 5(c), the resonator simultaneously confines optical WGM and breathing vibrational modes in the same area. The resonator is probed and driven by electrostatic actuation at its eigenmode. During the particle transits, the mechanical eigenmode is perturbed, depends on the position, density, stiffness, and size of the particles. This induced frequency fluctuations of mechanical resonance are optically read-out. Therefore, rapid detection of single particles is achieved, with a resolution of better than 20 μs and particle sensing resolution of 490 nm. In 2020, Yaras et al. also demonstrated an acousto-optic sensor for real-time magnetic resonance imaging (MRI).[149] In this work, Fiber Bragg gratings (FBG) are employed in the fiber core to generate a narrowband dielectric mirror, which is probed by a LiNbO\(_3\) transducer and immersed in water (Figure 5(d)). This transducer will react to the magnetic field captured by the solenoid coil, thus generating acoustic pressure on the FBG area. The reflection spectrums of the FBG can be reconstructed to extract the magnetic resonance imaging information. This FBG acousto-optical sensor was successfully tested in a 0.55 T prototype magnetic resonance imaging system as an active position marker.

### 3.2. Potential optomechanical sensing platforms

On top of inertial sensing, optomechanical devices promise new capabilities of quantum state control. Although in their infancy, these platforms open the door to the potential quantum and other precise sensing applications. Significant efforts have been made to realize the distributed quantum networks based on the optomechanical platform, which will not only enable quantum communication at a large scale but also export the possibility in microwave-optical photon entanglement and sensing mediated by gigahertz phonons. In 2020, Han et al. reported an integrated superconducting cavity piezo-optomechanical platform in which phonons are resonantly coupled with photons.[73] As depicted in Figure 6(a), a 10-GHz piezoelectric-driven microwave resonator is aligned on the top of an optical cavity. This design enables resonant enhancement of optomechanical and electromechanical interactions simultaneously. Based on the integrated interface between superconducting and nanophotonic circuits, a large \( C_{em} \sim 7 \) is achieved in this triply resonant piezo-optomechanical system.

Piezoelectric and electrostatic are the two most feasible approaches to probe the mechanical domain.[160–162] Nevertheless, as the most significant and mature photonic platform[163–165] and
many demonstrations in sensing applications, silicon does not exhibit a piezoelectric effect and is not effectively guide acoustic modes. Many existing realizations of light-sound coupling are built on unconventional material platforms. Recently, several approaches have been proposed for the demonstration of optomechanical interactions in the Si platform. For example, Munk et al. generated surface waves through absorption of modulated pump light in metallic gratings and thermo-elastic expansion. However, at present, the low acousto-optical efficiencies in their work limit technological readiness. Another solution is by the combination of piezoelectric film on top of the Si platform. In 2020, E. A. Kittlaus et al. demonstrated electro-

Figure 6. Potential optomechanical sensing platform. (a) Superconducting cavity piezo-optomechanical system. (b) Integrated acousto-optic platform in silicon photonics. (c) Injection locked electro-optomechanical system.
optomechanical modulation in silicon photonic waveguides on the AlN-on-SOI platform. As depicted in Figure 6(b), the SAW transducer is patterned on top of the AlN film, and the generating elastic wave extends into the optical waveguide layer. This incident wave with the frequency of $\Omega$ will modulate light wave at frequency $\omega_p$ and transfer the energy to optical sidebands at frequencies $\omega_p \pm \Omega$. A distributed, non-reciprocal acousto-optical modulator is developed with insertion losses of less than 0.6 dB and non-reciprocal contrast larger than 12 dB, envisaged to offer a pathway to applications including on-chip heterodyne detection and sensing.

The inherent nonlinearity, harnessed in the optomechanical radiation-pressure interaction, namely, as the radiation-pressure increase, the conservative force is not proportionally increased, can be used to explore synchronization effects. Based on this, enhanced scalability is possible for future applications involving arrays of injection-locked precision sensors. In 2017, Bekker et al. firstly demonstrated a radiation-pressure-driven optomechanical system actuated and locked by an integrated electrical interface. The injection signal is employed to suppress the drift in the optomechanical oscillation frequency and reduce the phase noise by over 55 dBc/Hz at 2 Hz offset. The left of Figure 6(c) shows the micrograph of this silica microtoroid optomechanical cavity. The cavity is electrostatically probed by circular electrodes and optically probed by a tapered fiber. The right-top figure shows the comparison of power spectra of unlocked and locked oscillations. We can find that the oscillations are indeed locked and that the frequency drift is eliminated. The right-bottom figure shows plots of phase noise of different driving voltages, from which we can find that a significant suppression of phase noise when the oscillator is locked.

4. Molecular vibration detection in optomechanical sensing

From a broad view of optomechanical sensing, apart from the mentioned sensing mechanism relied on the vibrations of the sensors themselves (Section 2 and 3), we can also resort to the optical detection of molecular vibrations. These atom-level vibrations, varying from analyte to analyte, can be resonantly coupled to and detected by the photon, thus enables the selectively sensing of molecules species and concentration. Additionally, light-induced temperature change, resulting from the transition from photon energy to phonon energy of lattice vibration, can be treated as another type of optomechanical sensing mechanism, which provides platforms for thermal-based sensors based on thermo-optics effect. During the past decades, several strategies, such as nanoantenna enhancement and all-optical photothermal sensing schemes, are employed for molecular vibration detection and thermal sensing on a chip. In this section, both the principle and enhancement schemes of this molecular vibration detection are discussed. Besides, its applications in optical modulators and sensors for physical, chemical, and biological sensing are introduced as well.

4.1. Nanoantenna-assisted infrared liquid and gas sensing

The nature of molecular vibration-induced infrared (IR) absorption spectrum has been investigated for decades to analyze the composition and concentration of the analyte in a non-invasive and non-destructive way, which is called IR spectroscopy technology. The vibration is excited by the wave nature of light, which is the time-varying electromagnetic field. Therefore, the resonance occurs when the frequency/wavelength of the exciting light match with the resonant frequency/wavelength of the vibrational mode of molecules. Therefore, the absorption peaks are shown at each resonant frequency/wavelength of the molecules in the frequency domain spectrum. The energy of chemical bonds and the interaction from the molecular structure determine the resonance modes and frequencies of molecular vibration. In the frequency domain, the different physical quantities of frequency, wavelength, and wavenumber have one-to-one mapping among each other. Even though they have different physical meanings, we can use any one of them to denote
and calculate others. According to the custom of the IR spectroscopy community, the wavenumber and the wavelength are mainly used to labeling the resonances of molecules. In this section, we use the wavenumber and the wavelength to denote the resonance in the spectrum. Most of the compounds hold the specific absorption spectrum in MIR range between 400 cm\(^{-1}\) (\(\lambda\): 2.5 \(\mu\)m) and 4000 cm\(^{-1}\) (\(\lambda\): 2.5 \(\mu\)m), which are divided into the functional group region (4000–1500 cm\(^{-1}\) or 2.5–6.6 \(\mu\)m) and the fingerprint region (1500–400 cm\(^{-1}\) or 6.6–25 \(\mu\)m). The absorption peaks in the functional group region represent the specific kinds of bonds in the molecules, which is used to characterize the functional group. In contrast, the absorption peaks in the fingerprint regions show complex modes of molecular vibration from symmetry or combination bands arising from multiple bonds deforming simultaneously, which can be treated as the ‘fingerprint’ of the molecules. With the development of Fourier transform infrared (FTIR) spectroscopy, the broadband IR spectrum can be obtained by performing the Fourier transform from the time-modulated broadband IR light emitting from an IR lamp. By placing the analytes into the light path of FTIR spectroscopy, the IR absorption spectrum can be captured and analyzed. However,
the intrinsic light-matter interaction in MIR is weak, which hinders the detection of molecular in small concentrations like sub-ppb level and short light path in subwavelength scale.

The strategy of surface-enhanced IR absorption (SEIRA) is proposed and demonstrated in 1980 by enhancing the localized electromagnetic field due to the collective electron resonance associated with the island nature of the thin metal film. Optical nanoantennas are resonant subwavelength nanostructures with a confined electromagnetic field near the surface. The resonance nature of nanoantennas can interact with the vibration nature of molecules when their resonance frequency/wavelength is matched or slightly detuned. This phenomenon is a kind of plasmon-phonon coupling and is first reported by F. Neubrech et al. in MIR in 2008. The resonance of IR nanoantennas can be easily engineered by controlling the topologies, and the localized electromagnetic field can be further enhanced by forming a two-dimensional periodic nanoantenna array with the sensitivity of 145 molecules per antenna. Several following works demonstrate the capability for monitoring the biomolecular monolayers with the surface functionalization of the gold nanoantenna.

4.2. IR liquid sensing using nanoantenna integrated with microfluidics and nanofluidics

To manipulate liquid samples into a microscale nanoantenna array, Adato propose a microfluidic integrated nanoantenna platform for detecting the biomolecules in the aqueous environment. As shown in Figure 7(a), the nanoantenna is fabricated on top of IR glass materials like CaF2. Then the chip is flipped-bonded to a PDMS microfluidic chamber to control the analytes flow through the surface of nanoantenna where the highest localized electromagnetic field exists. The IR light is shined from the backside of the nanoantenna chip, and the enhanced absorption spectrum is captured from the reflection signals from FTIR microscopy. With the microfluidic integrated nanoantenna chip-based platforms, different kinds of biomolecules are captured in several works, including protein, lipid and their dynamic interaction with nanoparticles. Since the lipid and protein hold different functional groups, dual resonance nanoantennas at 2900 cm$^{-1}$ (3.45 $\mu$m) and 1600 cm$^{-1}$ (6.25 $\mu$m) are designed to simultaneously detect amide I, II and CH$_2$, CH$_3$ stretching for polypeptides and lipid membranes, respectively. Figure 7(a) shows the dynamic monitoring of the biological process of melittin-induced membrane disruption and vesicular cargo release measured from a microfluidic integrated nanoantenna array.

To further minimize the volume of the analyte and enhance the electric field in sensing hot spots, Le et al. proposed a nanofluidic integrated nanoantenna sensing platform using the metal-isolator-metal (MIM) structure. Leveraging the vertical nanogap formed by chip bonding, the localized electric field and the area for sensing hotspots are enhanced and increased. By replacing the dielectric layer with liquid analytes, the ultrasensitive detection of fluidic samples is demonstrated with a sensitivity up to a molecular density of $7.1 \times 10^{-4}$ molecules $\AA^{-2}$. Some following work also investigates the optical properties of water in such nanoscale space using the nanofluidic integrated nanoantenna array. The critical fabrication technology for nanofluidic integrated nanoantenna is the stable bonding interface for IR glass materials. Such bonding technologies are developed in the semiconductor area for chip packaging, but the critical requirement for nanofluidic devices are the bonding strength and the stability under liquid stress corrosion. To gain high scalability, Xu developed a wafer-scale heterogeneous bonding technology of sapphire and silica to fabricate a nanofluidic nanoantenna array. The schematic drawing of the proposed hybrid nanofluidic SEIRA (HN-SEIRA) platform is shown in Figure 7(b). The linear polarized IR light is shining from the backside of the sapphire chip and transmit to the nanoantenna sensing chamber. The reflected light is captured to detect the resonance of the nanoantenna. When the wavelength of IR light matches with the resonance wavelength of a
nanoantenna, the light is absorbed, and the absorption value is affected by the resonance properties of nanoantennas, which are radiative loss and absorptive loss.

The temporal coupled-mode theory (TCMT) is derived to describe the resonance behavior of the nanoantenna, and the derived reflection spectrum is described as:

$$R(\omega) = j\left(\frac{\omega - \omega_0}{\omega - \omega_0} - \frac{\gamma_r - \gamma_a}{j(\omega - \omega_0) + (\gamma_a + \gamma_r)}\right)^2$$

(3)

where $\omega_0$ is the resonance frequency of nanoantenna and $\gamma_a$, $\gamma_r$ are absorptive and radiative loss of nanoantenna, respectively. This quotation describes the Lorenz line shape of nanoantenna resonance, and the reflection or absorption value is determined by the ratio of $\gamma_a$ and $\gamma_r$. When the critical coupling condition comes ($\gamma_a = \gamma_r$), the reflection is zero while the absorption is highest at 100% from Equation 2. The bandwidth or $Q$ factor of nanoantenna is affected by the sum of $\gamma_a$ and $\gamma_r$, which is the total loss in the plasmonic system. The lower the loss leads to the higher the $Q$ factor.

When we consider the effect of molecules coupling, the reflection spectrum of the system can be described as:

$$R(\omega) = j\left(\frac{\omega - \omega_0}{\omega - \omega_0} + \frac{H^2}{\omega - \omega_m + \gamma_m + \gamma_r + \gamma_m} - \frac{\gamma_r - \gamma_a}{j(\omega - \omega_0) + (\gamma_a + \gamma_r + \gamma_m)}\right)^2$$

(4)

where $\omega_m$ and $\gamma_m$ are the resonance frequency and absorptive loss of molecules. $\mu$ is the coupling coefficient between nanoantenna and molecules, denoting the coupling strength. Since the dipole moment of molecules is much smaller than that in nanoantenna, the resonance of molecules is considered as a dark resonator compared to nanoantenna resonance, which is a bright resonator. Therefore, we ignore the radiative loss of molecules and obtain Equation 3. This equation describes the resonance line shape of the reflection spectrum of nanoantenna coupled with molecules. When $\omega_0 = \omega_m$, the spectrum performs the electromagnetic-induced-transparent-like (EIT-like) line shape. As a contrast, the spectrum turns to Fano-like when $\omega_0 \neq \omega_m$. To quantify the sensing performance, the change of reflection with the introduction of molecules can be obtained as:

$$\Delta R(\omega = \omega_0) = R - R|_{\mu=0} = \left[\frac{\gamma_r' - \gamma_a'}{\gamma_r' + \gamma_a'}\right]^2 - \left[\frac{\gamma_r - \gamma_a}{\gamma_r + \gamma_a}\right]^2$$

(5)

where $\gamma_a' = \gamma_a + \mu^2/\gamma_m$. Thus, the dark mode of this system can be thought of as adding an amount of additional intrinsic damping loss to the bright mode, resulting in a leftward movement for the reflection dip along the reflection curve. The $\gamma_a'$ and $\gamma_r$ is tuned by the gap of the nano-fluidic channel, and the highest reflection change caused by O-H bending at 3333 cm$^{-1}$ (3.0 $\mu$m) is achieved when the nanogap is 55 nm, which is shown in Figure 7(b). Even though the smaller gap of 30 nm provides a higher electric field enhancement, the nature of coupled system between nanoantennas and molecules dominates where the loss of two resonators plays an essential role in the resonance spectrum. With the optimization approach of loss engineering, an ultra-high sensitivity (0.8364 pmol$^{-1}$ %) is achieved by demonstrating dynamic fluidic monitoring of acetone and water. Additionally, the capillary force in nanoscale space can help to self-drive the liquid flow into the sensing hotspot without external power, an excellent platform for liquid sensing.
of small molecules in sub-nanometer-scale like alcohol ketone, sugar, and other organic and inorganic liquids with simple molecular structures.

The methods of loss engineering to tune the resonance properties are proposed by Wei et al. in 2019.[188] Despite tuning the absorptive and radiative loss by the gap of the dielectric layer from MIM structures, the radiative loss can be independently tuned by folding the planar nanoantenna structure as shown in Figure 7(c). The reflection and transmission spectrum of planar nanoantenna can be derived from TCMT:

\[
T(\omega), \ R(\omega) = \left| \frac{j(\omega - \omega_0) + \gamma_a r + \mu^2 j(\omega - \omega_m) + \gamma_m}{j(\omega - \omega_0) + (\gamma_a + \gamma_r) + \mu^2 j(\omega - \omega_m) + \gamma_m} \right|^2
\]  

(6)

All parameters denote the same meaning as Equation 3. Similarly, the change of transmission and reflection signal can be calculated as:

\[
\Delta T(\omega = \omega_0) = \frac{2\mu^2}{\gamma_a \gamma_m (1 + f)^3} f
\]  

(7)

\[
\Delta R(\omega = \omega_0) = -\frac{2\mu^2}{\gamma_a \gamma_m (1 + f)^3} f^2
\]  

(8)

where \( f = \gamma_r / \gamma_a \) defining the ratio of radiative and absorptive loss. The negative sign in Equation 7 indicates the opposite change in transmission and reflection spectrum induced by molecules’ vibration. \( \gamma_a \) refers to the omics loss of material. By applying the first derivative of \( f \) for Equations 6 and 7, the maximum enhancement of the \( T \) and \( R \) spectrum can be calculated as the optimal condition when \( f \) equals 0.5 and 2, respectively. A 20 nm-thin poly(methyl methacrylate) (PMMA) layer is used to characterize the sensing performance of crooked nanoantenna. Molecule signals are increased by 25 times, reaching an experimental enhancement factor of \( 2.8 \times 10^4 \). The maximum sensitivity is achieved at devices S8 and S6 for transmission and reflection mode, respectively. Despite the loss engineering method, the most common methods to improve the sensitivity of nanoantennas are to increase the electric field by narrowing the gap of two adjacent antennas[182,210] and increasing sensing hotspot area by undercut the nanoantenna.

In addition to sensitivity, the bandwidth is another key figure of merit (FOM) for nanoantenna sensors since the nanoantenna can only enhance the molecule absorption near the absorption frequency/ wavelength based on Equations 3 and 5. Self-similar fractal structures are used to broaden the bandwidth by different order resonance modes.[181,198,211–217] Figure 7(d) shows a Sierpiński fractal nanoantenna with the order of 2 proposed by D. Hasan et al.[189] By harnessing the broadband electric field enhancement of the modified fractal patterns originating from the lightning rod effect in the non-resonant regime, the substantial enhancement of molecular absorption at MIR was demonstrated by the fractal patterns non-resonant regime even under extreme thermal broadening. Another approaches to achieve broadband resonance is the bright-dark coupling. Similar to the interaction between the nanoantenna and molecules, the dark coupler can be made by adjusting the radiative loss of the nanoantenna.[184,218] The bright and dark antenna form a new resonance system with two resonance wavelengths, and these two resonance peaks can further couple with molecules absorption. In contrast, post-fabrication tuning is another strategy to achieve multiple resonances of nanoantenna sensors at different times. Different tuning methods are developed including incident angle,[219,220] polarization,[218,221] phase change materials,[222,223] 2 D materials,[194,196,224–228] and MEMS.[229–232]
4.3. IR gas sensing using nanoantenna integrated with enrichment coating

The IR absorption of gases plays a significant role in our life. For example, greenhouse gases absorb the energy from sunlight to keep global warming. Unfortunately, the concentration of greenhouse gases like CO₂, NOₓ, SO₂, CH₄ keep increasing nowadays due to the consumption of carbon-based fuels. The most intuitive way to monitor greenhouse gases is the IR spectroscopy technology, which harnesses the high absorption of these gases in MIR. Additionally, the volatile organic compounds (VOCs) also show unique fingerprint absorption in MIR, which is potential for breath analysis for clinical diagnosis. The nondispersive infrared (NDIR) sensor is commonly used to distinguish gases by applying a narrow band filter to a broadband light source. However, one of the drawbacks of NDIR sensors is the long optical path for light-matter interaction to generate a measurable absorption signal. With the miniaturization efforts using MEMS technology, the optical path is reduced to 10 mm for 4–5% CO₂ detection, which is still bulky and insensitive. IR nanoantenna with subwavelength optical path and enhanced absorption of molecules become the perfect candidate for IR spectroscopic gas sensing. However, the density of gas molecules is generally lower than liquid and solid samples meaning the much fewer molecules in a unit volume, which hinders the interaction between nanoantenna and molecules occurring at the nanometer scale space near the sensor surface. The gas enrichment layer is proposed to enrich the gas molecules on to sensor surface locally with physical adsorption or chemical reaction. PEI is a kind of active polymer that can react with CO₂ and is widely used to enhance the sensitivity of CO₂ gas sensors. Detailed chemical reactions involved as CO₂ reacts with the primary and secondary amines of the branched PEI polymer chain are as below:

\[
\begin{align*}
\text{CO}_2 + 2\text{RNH}_2 & \leftrightarrow \text{RNHCOO}^- + \text{RNH}_3^+ \quad (9) \\
\text{CO}_2 + 2\text{R}_2\text{NH} & \leftrightarrow \text{R}_2\text{NCOO}^- + \text{R}_2\text{NH}_2^+ \quad (10) \\
\text{CO}_2 + \text{R}_2\text{NH} + \text{R'}\text{NH}_2 & \leftrightarrow \text{R}_2\text{NCOO}^- + \text{R'}\text{NH}_3 \quad (11) \\
\text{CO}_2 + \text{R}_2\text{NH} + \text{R'}\text{NH}_2 & \leftrightarrow \text{R'}\text{NCOO}^- + \text{R}_2\text{NH}_2^+ \quad (12)
\end{align*}
\]

Hasan et al. first implemented the PEI thin film onto the MIR nanoantenna to form a hybrid metamaterial platform for gas sensing. With the confined electromagnetic field by nanoantenna, the optical path can be reduced to a subwavelength scale while the detection range is within the sub ppm concentration of CO₂. A CMOS-compatible nanoantenna platform with MIM configuration by Mo-AlN-Mo is developed for mass production. With the adsorption of CO₂, the chemical properties of the PEI layer change, resulting in the new absorption peaks at μm in the MIR spectrum. By heating the device in an N₂ environment, the CO₂ is desorbed, and PEI returns to the initial state. The response and recovery time are s and s, respectively. In addition to metallic nanoantennas, the PEI-hybrid platform on the all-dielectric photonic crystal is also developed by Chang et al., leveraging the resonance-assisted transmission. The experimental detection limit is achieved by 20 ppm, leading to transmission mode detection in low-loss all-dielectric structures as a surface enhancement method.

In addition to chemical adsorption, physical adsorption or physisorption is another strategy to trap molecules in a confined area. 2D materials like graphene, phosphorene, and moly-disulfide (MoS₂) show great potential for gas adsorption and plasmonic materials. According to the semi-metal properties, graphene is also a promising plasmonic material with an ultra-confined electromagnetic field due to its intrinsic 2D structure. Hu et al. demonstrated an all-in-one platform where graphene serves as a plasmonic material and gas trapping material simultaneously in the same structure. The label-free identification of gas molecules SO₂, NO₂, N₂O, and NO is achieved by detecting their rotational-vibrational modes using graphene plasmon. Figure 8(c) shows the experimental setup and testing results of SO₂ absorption at 1347 and 1374 cm⁻¹ (7.42 and 7.27 μm). With the aid of fast response time (<1 min), the real-time monitoring of gaseous chemical reaction between NO and O₂ is
demonstrated by directly investigate the fingerprint absorption of reaction byproduct NO₂. The reduction of NO and increment of NO₂ is dynamically measured by their fingerprint absorption peaks at 1838 and 1906 cm⁻¹ (5.44 and 5.24 μm) as well as 1590 and 1610 cm⁻¹ (6.28 and 6.21 μm), respectively. The hybrid nanoantenna platforms combining graphene and gold nanoantenna are also proposed for gas sensing applications. However, the physisorption caused by such 2D material is still limited due to the limited volume, which bypasses the utilization of the 3rd dimension of the space. The metal-organic framework (MOF) is a 3D porous structure producing a cage-like space for gas molecules to sit. Zhou et al. first introduce ZIF-8 MOF to nanoantenna sensing platform with proper design of dual-band nanoantenna resonance fitting to CO₂ and CH₄ absorption wavelength of 2347 cm⁻¹ (4.26 μm) and 1305 cm⁻¹ (7.66 μm). Since the kinetic diameter of CO₂ and CH₄ are 3.3 and 3.8 Å,

Figure 8. All-optical plasmon-phonon coupling for Gas detection of MIR metamaterial sensors. (a) PEI as gas enrichment layer used for plasmonic nanoantennas; (b) PEI as gas enrichment layer used for all-dielectric metamaterials; (c) Graphene as gas enrichment layer; (d) MOF as gas enrichment layer used for plasmonic nanoantennas.
Table 4. The summary of optomechanical sensors for molecular vibration detection.

| Sensing unit | Sensing type | Limit of Detection | Sensing analytes | Wavenumber (cm$^{-1}$) | Reference |
|--------------|--------------|--------------------|------------------|------------------------|-----------|
| Nanorod      | Thin-film    | 2 nm               | Silk protein     | 1537, 1660             | 2009, [178]|
| Split ring resonator | Thin-film | Monolayer          | ODT              | 2880                   | 2009, [179]|
| FRAMM        | Thin-film    | Monolayer          | IgG antibody     | 1537, 1660             | 2012, [180]|
| Trapezoidal nanoantenna | Thin-film | Monolayer          | AT-G6-COOH       | 1139, 1200, 1400, 1434, 1627 | 2013, [181]|
| Semiconductor nanoantenna | Thin-film | 50 nm              | PMMA             | 752, 810, 827, 842     | 2013, [183]|
| Nanorod      | Thin-film    | 8 nm               | PMMA             | 1730                   | 2013, [184]|
| Nanorod      | Microfluidics| Monolayer          | IgG antibody     | 1537, 1660             | 2013, [187]|
| Nanorod      | Thin-film    | 50 nm              | PMMA             | 1140, 1250, 1450, 1720 | 2013, [191]|
| Fan-shape nanoantenna | Thin-film | Monolayer          | ODT              | 2850–2995              | 2015, [192]|
| Graphene nanoribbon | Thin-film | Monolayer          | IRRAS            | 1537, 1660             | 2015, [194]|
| Nanorod      | Microfluidics| Monolayer          | lipid membrane  | 2850–2950              | 2016, [196]|
| Graphene nanoribbon | Thin-film | 1.5 nm             | PMMA             | 1151, 1192, 1244 and 1269 | 2016, [196]|
| Quasi-3D nanoantenna | Thin-film | Monolayer          | ODT              | 2850–2995              | 2017, [197]|
| Plasmonics – Nanofluidics Hybrid | Nanofluidics | 4.4 $\times$ 10$^{-4}$ molecules Å$^{-2}$ | C$_{18}$H$_{38}$ | 2850, 2930 | 2017, [199]|
| Bowtie nanoantenna | Thin-film | Monolayer          | 4-NTP            | 1515, 1335             | 2017, [201]|
| Double-layer graphene | Thin-film | Monolayer          | GNRA             | 1600                   | 2017, [224]|
| Nanorod on waveguide | Thin-film | Monolayer          | ODT              | 2850–2995              | 2018, [159]|
| Self-similar nanorod | Microfluidics | Monolayer | lipid GABA Melittin | 1537, 1660, 2850–2950 | 2018, [159]|
| Hybrid Graphene nanorod | Thin-film | 200 pM             | Glucose          | 1300–1500              | 2018, [226]|
| Cross nanoantenna | Gas         | 20 ppm             | CO$_2$           | 1200–2000              | 2018, [237]|
| All-dielectric slab | Gas         | 20 ppm             | CO$_2$           | 1200–2000              | 2018, [240]|
| Crooked nanoantenna | Thin-film | 20 nm              | PMMA             | 1720                   | 2019, [188]|
| Graphene nanoribbon | Gas         | 800 ppm            | SO$_2$ NO NO$_2$ | 1200–1500              | 2019, [253]|
| Hybrid Graphene Nanorod | Thin-film | Monolayer          | IgG antibody     | 1537, 1660             | 2019, [227]|
| Plasmonics – nanofluidics hybrid nanoantenna | Nanofluidics | 0.29% | Water, Ethanol, Acetone | 2800–4000 | 2020, [235]|
| Nanodisk      | Thin-film    | 7 nm               | miR-155          | 1700                   | 2021, [185]|

INTERNATIONAL JOURNAL OF OPTOMECHATRONICS 141
respectively, CH\textsubscript{4} is only adsorbed in the cavity (diameter: 11.6 Å), while CO\textsubscript{2} can enter the pore aperture (diameter: 3.4 Å). It indicates that most of the CO\textsubscript{2} and CH\textsubscript{4} are captured in different areas of the ZIF-8. Therefore, the competition between CO\textsubscript{2} and CH\textsubscript{4} in ZIF-8 is relatively small, which is a critical characteristic for the simultaneous detection of the gases. The MOF–SEIRA platform demonstrated simultaneous on-chip sensing of CO\textsubscript{2} and CH\textsubscript{4} with fast response time (< 60 s), high accuracy (CO\textsubscript{2}: 1.1%, CH\textsubscript{4}: 0.4%), small footprint (100 × 100 μm\textsuperscript{2}), and excellent linearity in wide concentration range (0–2.5 × 10\textsuperscript{4} ppm).

The marriage between nanoantennas and gas enrichment layers solves the problems of inducing small numbers of gas molecules into ultra-confined sensing hot spots of nanoantennas, remaining the enhanced sensitivity by plasmonic resonance and intrinsic selectivity by IR fingerprint absorption from molecular vibration. The translation from the mechanical vibration of molecules to the IR absorption spectrum provides a natural probe to analyze molecule species. Such a hybrid IR vibrational sensing platform opens up the possibilities of miniaturized gas identification with high sensitivity and high selectivity for a diversified application like in-breath diagnosis, environmental monitoring, biological metabolic analysis, fire or gas leakage detection, and other IoT based gas sensing systems (Table 4).

4.4. All-optical photothermal sensing

In addition to enhance the optical absorption of molecular vibration by nanoantennas at the sensing stage, the photothermal effect is an emerging technology that can be leveraged to
improve the performance at the sensing signal readout stage. The photothermal effect is a phenomenon associated with electromagnetic radiation. It is produced by the photoexcitation of material, resulting in the production of thermal energy (heat). Such thermal effects can depend on multiple properties of the material, in particular on the absorption coefficient, the thermal conductivity, the temperature dependence of the RI, and photoelastic coefficients. In the last section, we explained the nature of absorption of light by molecules’ vibration. In this part, we further investigate the energy transformation and the effects on material optical properties. To begin with, we should focus on the concept of optical absorption. Light-matter interaction is a global term to describe the behavior when light meets matter. According to the particle nature of light, the quantization of energy can be treated as the accumulation of photon energy, which is a function of frequency/wavelength. The unit amount of quantized energy (energy of a photon) can be expressed as:

\[
E = hf = \frac{hc}{\lambda}
\]  

(13)

where \(h\) is Plank’s constant, \(f\), \(\lambda\), \(c\) are the frequency, wavelength, and speed of light, respectively. For long wavelength or low frequency of light, the photon energy is small so that the light-matter interaction tends to be the excitation of rotational (majority optical band: microwave, terahertz, far infrared) and vibrational resonance (majority optical band: infrared and visible) for most of the molecules and atoms. For short-wavelength or high frequency of light, the photon is able to excite the electron from valence band to conduction band when photon energy is larger than the bandgap, called the vibronic transition. For the metallic materials without a bandgap, the electron is freely excited, resulting in broadband absorption. The excitation of electron migration and rotational or vibrational resonance may cause the energy exchange from photon energy to phonon/thermal energy, called absorption. The phonon energy performs complex behavior among different materials. In this review, we mainly focus on the most global effect, which is the temperature change. The temperature affects the RI of the material, which determines the speed of light traveling in the medium and the reflection and transmission properties at the material interface. The temperature-induced RI change can be read out by various optical systems in free space,\(^{248–253}\) fiber optics,\(^{254–257}\) and waveguides.\(^{258–266}\)

The free-space all-optical photothermal sensing is promising for extensive area imaging of biological samples and materials specimens. Figure 9(a) shows widefield photothermal sensing (WPS) microscope based on the reflection change from normal incidence. There are two light beams in the WPS microscope system. One is pump light using for the introduction of photothermal effect to heat the specimen. The other is probe light for detection of temperature-induced RI change by normal incidence. Bai et al. wisely select the wavelength of the pump and probe light to make full use of the advantages of the different optical bands.\(^{248}\) IR light carries information of vibration fingerprint of molecules, but the detection of IR light is still challenging in widefield, small resolution, and high speed. The detection of visible light is much mature for high-throughput, widefield sensing. Therefore, the IR laser is selected as pump light for introducing fingerprint absorption of a specimen, while the visible light-emitting diode (LED) is chosen as probe light to read out the temperature-induced RI change in widefield and high-speed with a CMOS imaging sensor. Generally speaking, the sample should be highly absorptive under pump light to induce heat but non-absorptive under probe light to capture the temperature-induced RI change. The reflection of probe light can be analyzed by Snell’s law with near-normal incident approximation by considering the air-sample interface and sample substrate interface and ignoring the sample absorption from probe light. The dispersion relationship can be expressed as:

\[
R(\lambda) = \frac{r_1^2 + r_2^2 + 2r_1r_2\cos(2k_0n_1(\lambda)d)}{1 + r_1^2r_2^2 + 2r_1r_2\cos(2k_0n_1(\lambda)d)}
\]  

(14)
where \( r_1(\lambda) = \frac{n_0(\lambda) - n_1(\lambda)}{n_0(\lambda) + n_1(\lambda)} \) and \( r_2(\lambda) = \frac{n_1(\lambda) - n_2(\lambda)}{n_1(\lambda) + n_2(\lambda)} \) are reflections as a function of RI \( n(\lambda) \) of the material at the two interfaces, and \( d \) is the thickness of the sample. The subscripts 0, 1, and 2 refer to the media of air, sample, and substrate, respectively. When the pumping IR beam is absorbed by the sample, heat is produced, and the maximum temperature increase can be described as \( \Delta T \propto \sigma I_{IR}/\rho C \), where \( \sigma \) is the absorption coefficient, \( I_{IR} \) is the pump beam intensity, and \( \rho \) and \( C \) are the density and heat capacity of the sample, respectively. The temperature rise \( \Delta T \) will induce a RI change and a thermal expansion of the sample: \( n'(\lambda) = n(\lambda) + \alpha \Delta T \) and \( d' = d(1 + \beta \Delta T) \). Here, \( \alpha \) is the thermo-optic coefficient, and \( \beta \) is the thermal expansion coefficient (TEC). The photothermal image is then detected by the difference of the reflection with and without pump light (\( R' \) and \( R \)). Despite reflection detection of the probe light, the transmission is also able to be measured by propagation phase change of probe light, as shown in Figure 9(b). Zhang et al. proposed a bond-selective transient phase (BSTP) imaging to extract the molecular vibrational absorption image at 50 Hz frame rate with high spectral fidelity, sub-microsecond temporal resolution, and sub-micron spatial resolution.\(^{[249]}\) The threshold pump power for this technology is mainly limited by the camera performance since the absolute power change of probe light is detected. Furthermore, the plasmonic photothermal (PPT) effect is used to enhance the thermal response of the pump light, and localized surface plasmon resonance (LSPR) is used to enhance the response to the thermo-optical effect from the probe light. G. Qiu et al. developed an ultrasensitive photothermal sensing platform combining PPT and LSPR for detection of the selected sequences from severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) through nucleic acid hybridization (Figure 9(c)).\(^{[251]}\) The lower detection limit of the virus achieves 0.22 pM with precise detection of the specific target in a multigene mixture. Therefore, the free-space all-optical photothermal platform paves the way to ultrasensitive, high-throughput, fast-response imaging for physical sensing, chemical sensing, and biosensing.
The fiber all-optical photothermal sensing allows point-of-care diagnosis with high sensitivity thanks to the light confinement of optical fiber. Figure 9(d) shows a WGM microresonator-based single-particle double-modulation photothermal absorption spectroscopy.\textsuperscript{[257]} The pump light is directly shining on the WGM microresonator to induce \textit{in-situ} temperature change. The probe light is traveling through an optical fiber coupling with a WGM microresonator. Photothermal shifts are resolved in the resonance frequency of the microresonator smaller than 100 Hz, orders of magnitude smaller than previous WGM sensing schemes. With the plasmonic-enhanced absorption from a single gold nanorod, the series of Fano resonance peaks from the coupling between the LSPR of the gold nanorod and the WGMs the resonator can be read out. In addition to the WGM coupling the light from fiber, Wang et al. proposed a photothermal platform using a microfiber resonator assisted by graphene.\textsuperscript{[255]} The pump light circulates in the resonator can interact with the graphene wrapping around the fiber, enhancing the photothermal effect with modulation efficiency of 71 pm/mW. Beyond the modulation and switching of the probe light, Y. Liu et al. proposed a plasmonic fiber-optic photothermal anemometer with carbon nanotube (CNT) coating.\textsuperscript{[254]} In contrast with the previous photothermal platform to minimize the heat dissipation for localized temperature increase, this platform utilizes gas to release the photothermal energy by convection and measure the remaining heat to reflect the gas speed. The system is achieved by fiber Bragg grating-assisted SPR sensor as a photothermal conversion element. After inducing heat by a pump laser from a tunable laser source, the temperature of the SPR sensing area is increased. The probe light from a broadband source is used to read out the temperature change. In this system, the gas is induced to perform as a heat sink to the sensing area. The larger gas flow rate takes more thermal energy by convection, and the temperature is reduced. With this anemometer, the dynamic range of 0.05–0.65 m/s wind speed is measured in real-time with a simple and robust structure.

The guided wave photothermal platform offers ultra-confined light and miniaturized systems on a chip. Figure 10(a) shows the system schematic of an on-chip photothermal sensor array achieved by photonic microdisk resonators with attached absorbers.\textsuperscript{[264]} The pump light is delivered perpendicularly to the absorber to induce the temperature change on the microdisk resonator. The probe light is traveling in the waveguide circulating in a cascaded microdisk resonator. The resonance wavelength is highly dependent on the RI of the disk, which is affected by the temperature owing to the thermo-optics effect. The wavelength shift from the resonance peak can be read out according to the absorbed thermal power. Photothermal spectroscopy is demonstrated by Vasiliev et al. on a microring resonator, shown in Figure 10(b).\textsuperscript{[259]} The pump light is selected in the MIR wavelength from 2777 cm\textsuperscript{-1} to 3076 cm\textsuperscript{-1} (3.25–3.6 \textmu m) to produce the absorption from molecular vibration. The absorbed light introduces the thermo-optic effect on the Si microring resonator to shift resonance frequency. The change can be detected by the power drop from the probe light. The measured absorption spectrum of AZ5214 photoresist from the proposed thermal spectroscopy agrees well with the spectrum captured by FTIR spectroscopy. For microdisk/ring resonator, the threshold power is limited by the Q factor of the optical resonator. When the Q factor is large, the threshold power decreases due to the sharp peak. However, at the same scenario, the sensing resolution of pump power/temperature also increases since the same probe signal corresponds to small pump power. However, the thermo-optic effect on the waveguide material is limited. Therefore, some other materials are added to the waveguide to form hybrid platforms with a better thermo-optic response. The MEMS resonator is integrated with a microring resonator to perform as a temperature reporter according to the resonant frequency shift.\textsuperscript{[260]} As shown in Figure 10(c), the MEMS resonator is excited by the optical gradient force from the pump light in the photonic microring resonator. Sensing light is used to induce heat to the MEMS absorber in normal incidence or in the waveguide. The modulation frequency shift is read out by a probe light in the waveguide. Optical interaction between microring resonator and MEMS resonator change a lot at different vibration positions with different sensing light power.
Bimorph thermal beam is also implemented with the photonic waveguide for photothermal sensing.\[^{261}\] With the thermal displacement from the bimetallic thermal beam, the light intensity is modulated by the interaction between the waveguide and nanowire. Despite MEMS structures, MXene is a class of 2D materials with excellent thermal and optical properties. By integrating Ti\(_3\)C\(_2\)T\(_x\) MXene with photonics MZI, the photothermal induced RI change of MXene introduces the phase shift on one arm of MZI, resulting in the change of power splitting ratio in 2 output channels.\[^{263}\] In summaries, the photonics waveguide platform for all-optical photothermal sensing provides an ultrasensitive and ultrafast response with compact device sizes.

5. Summary and outlook

In summary, a comprehensive review of micro/nano optomechanical sensors development has been presented. In general, it can be categorized into three major fields of development according to their configurations. First is the most developed current passive optomechanical sensors with applications in physical sensing, second is the electrically modulated optomechanical sensing platforms with huge potential, while third is the nanoantenna-assisted molecular vibration level sensing and all-optical photothermal sensing. The current passive optomechanical sensors started with cantilever configurations in the early years, then extended to other configurations such as membranes and coupled nanocavities. The main applications of these optomechanical sensors are found in physical sensing, including force, displacement, inertia, and acoustic, etc.\[^{267}\] Then, to add the tunability to the whole optomechanical systems, tuning mechanisms such as acousto-optical tuning through piezoelectric effect and electrostatic effect have been proposed, providing an extra degree of freedom for the sensing systems. Lastly, leveraging the interactions between molecular bonds vibrations and optical resonance, molecular vibrational sensing with nanoantenna assistance has been proven as an emerging field for chemical and biological sensing due to excellence in low detection limit, enhanced sensitivity, and compact footprint. The photothermal effect, a novel strategy to improving the sensing signal readout, is introduced as well.

Compared with sensors with electrical output, optomechanical sensors provide superior advantages of high sensitivity, low limit of detection, and immunity to electromagnetic interference. Leveraging the optomechanical effect, physical excitations that are firstly converted to mechanical vibrations through cantilevers in \(\mu\text{m}\) to \(\text{nm}\) scale, then the corresponding mechanical signal is coupled to optical resonance to achieve a highly sensitive detection. Among various optomechanical sensors for physical sensing, we see that cantilevers are still used as primary structures that perform the mechanical to optical coupling purpose. Depending on the configurations, photonic crystal based optomechanical sensors and microdisk cavity based optomechanical sensors can be found in AFM, displacement, acoustic, ultrasound, and inertia sensing applications. At the same time, other configurations of optomechanical sensors, including nanobeam-based and membrane-based, which are aimed at physical sensing, have been developed. With the ever-increasing process fabrication capabilities, we can expect further miniaturization and higher sensitive optomechanical sensors to be developed.

Electro-optomechanical platforms provide efficient access for further probing optomechanical cavities by the radiofrequency signal, thus the tunability of the optomechanical systems. Apart from its major endeavors in the demonstration of quantum network circuits, electro-optomechanical platforms provide more degree of freedom to enhance the sensing capability and are envisaged to offer a pathway for precise sensing applications with sensitive readout in the optical domains. Moreover, the coherent interaction between acoustic phonons and photons also offers excellent possibilities for inertial sensing without movable structure and working at the quantum ground state of the micromechanical resonators. In the last decade, primitive sensing demonstrations have been performed based on piezoelectric-driven or electrostatic-driven optomechanical platforms with unique advantages in both inertial sensing and non-inertial sensing applications.
Many leading efforts aimed to explore the novel schemes and applications of electro-optomechanical systems are currently underway. Although in their infancy, these platforms open the door to potential quantum and high-precise sensing applications.

For vibrational sensing of IR molecular fingerprint, optical nanoantennas provide a novel sensing platform with miniaturized size, enhanced sensitivity, and lower detection limit with the aid of micro/nanofluidic for liquid molecules and enrichment layer for gas molecules. The bandwidth of the nanoantenna device needs to be further improved to cover a wide wavelength range in the MIR fingerprint region. Additionally, artificial intelligence can be a powerful tool to design nanoantenna structures in an inverse way and to analyze sensing data with high accuracy for molecular identification. Furthermore, despite the single-point measurement, nanoantennas can also be used in IR imaging for biological samples and material specimens for the enhanced absorption signal. Leveraging hyperspectral imaging, massive information from molecules vibration can be extracted by nanoantenna enhancement, paving the way to next-generation IR imaging of monolayer biomolecules, single-cell imaging, dynamic monitoring for metabolisms. For all-optical photothermal sensing, three types of sensing platforms with free-space, fiber-optics, and guided-wave configuration are reviewed and summarized. Combining the photothermal and thermo-optics effects into one optical system, various applications are demonstrated, including all-optical switching, photothermal modulation, radiation/temperature sensing, biosensing, and hyperspectral imaging. Furthermore, the photothermal effect can be further enhanced by inducing the metamaterial absorbers. With the engineered nanostructures, the photothermal effect can be tailored according to the optical properties of pump light like wavelength, incident angle, polarization, angular momentum. Additionally, the thermo-optic effect can also be enhanced in terms of efficiency and response time by adding novel materials like 2D materials and phase change materials. In the future, with the improvement in photothermal and thermo-optical effects, the all-optical photothermal platform will benefit the advanced function, including ultrafast optical communication, all-optical neuron network, compact spectroscopic chemical, and biological sensing systems.

**Funding**

The authors acknowledge financial supports from the NRF-CRP15-2015-02 “Piezoelectric Photonics Using CMOS Compatible AlN Technology for Enabling the Next Generation Photonics ICs and Nanosensors”, NRF2015-NRF-ISF001-2620 “Reconfigurable data center optical interconnects using fast nanophotonic MEMS waveguide switches” and RIE2020-AME-2019-BRENAIC [A18A5b0056] “Brain-Efficient Nanomechanical Artificial Intelligence Computing” at National University of Singapore, Singapore.

**References**

[1] Wu, M.C.; Solgaard, O.; Ford, J.E. Optical MEMS for lightwave communication. *J. Lightwave Technol.* 2006, 24, 4433–4454. DOI: 10.1109/JLT.2006.886405.

[2] Motamedi, M.E. Micro-opto-electro-mechanical devices and on-chip optical processing. *Opt. Eng.* 1997, 36, 1282–1285. DOI: 10.1117/1.601356.

[3] Lee, C.; Lin, Y.S.; Lai, Y.J.; Tasi, M.H.; Chen, C.; Wu, C.Y. 3-V driven pop-up micromirror for reflecting light toward out-of-plane direction for VOA applications. *IEEE Photon. Technol. Lett.* 2004, 16, 1044–1046. DOI: 10.1109/LPT.2004.824964.

[4] Lee, C. Design and fabrication of epitaxial silicon micromirror devices. *Sens. Actuat. A Phys.* 2004, 115, 581–590. DOI: 10.1016/j.sna.2004.03.045.

[5] Lee, C.; Lai, Y.J.; Wu, C.Y.; Yeh, J.A.; Huang, R.S. Feasibility study of self-assembly mechanism for variable optical attenuator. *J. Micromech. Microeng.* 2005, 15, 55–62. DOI: 10.1088/0960-1317/15/1/009.

[6] Chen, C.; Lee, C.; Yeh, J.A. Retro-reflection type MOEMS VOA. *IEEE Photon. Technol. Lett.* 2004, 16, 2290–2292. DOI: 10.1109/LPT.2004.833964.
[7] Lee, C.; Andrew Yeh, J. Development of electrothermal actuation based planar variable optical attenuators (VOAs). J. Phys. Conf. Ser. 2006, 34, 1026–1031. DOI: 10.1088/1742-6596/34/1/170.

[8] Lee, C. MOEMS variable optical attenuator with improved dynamic characteristics based on robust design. IEEE Photonics Technol. Lett. 2006, 18, 773–775. DOI: 10.1109/LPT.2006.871108.

[9] Lee, C. Monolithic-integrated 8CH MEMS variable optical attenuators. Sens. Actuat. A Phys. 2005, 123–124, 596–601. DOI: 10.1016/j.sna.2005.04.032.

[10] Lee, C.; Wu, C.Y. Study of electrothermal V-beam actuators and latched mechanism for optical switch. J. Micromech. Microeng. 2005, 15, 11–19. DOI: 10.1088/0960-1317/15/1/003.

[11] Chew, X.; Zhou, G.; Yu, H.; Chau, F.S.; Deng, J.; Loke, Y.C.; Tang, X. An in-plane nano-mechanics approach to achieve reversible resonance control of photonic crystal nanocavities. Opt. Express. 2010, 18, 22223–22244. DOI: 10.1364/OE.18.022232.

[12] Chew, X.; Zhou, G.; Chau, F.S.; Deng, J.; Tang, X.; Loke, Y.C. Dynamic tuning of an optical resonator through MEMS-driven coupled photonic crystal nanocavities. Opt. Lett. 2010, 35, 2517–2519. DOI: 10.1364/OL.35.002517.

[13] Chew, X.; Zhou, G.; Chau, F.S.; Deng, J. Nanomechanically tunable photonic crystal resonators utilizing triple-beam coupled nanocavities. IEEE Photon. Technol. Lett. 2011, 23, 1310–1312. DOI: 10.1109/LPT.2011.2164054.

[14] Seok, T.J.; Quack, N.; Han, S.; Muller, R.S.; Wu, M.C. Large-scale broadband digital silicon photonic switches with vertical adiabatic couplers. Optica 2016, 3, 64. DOI: 10.1364/OPTICA.3.000064.

[15] Qiao, Q.; Yazici, M.S.; Dong, B.; Liu, X.; Lee, C.; Zhou, G. Multifunctional mid-infrared photonic switch using a MEMS-based tunable waveguide coupler. Opt. Lett. 2020, 45, 5620–5623. DOI: 10.1364/OL.400132.

[16] Zhou, G.; Chau, F.S. Micromachined vibratory diffraction grating scanner for multiwavelength collinear laser scanning. J. Microelectromech. Syst. 2006, 15, 1777–1788. DOI: 10.1109/JMEMS.2006.886027.

[17] Du, Y.; Zhou, G.; Cheo, K.K.L.; Zhang, Q.; Feng, H.; Chau, F.S. A 21.5 KHz high optical resolution electrostatic double-layered vibratory grating laser scanner. Sens. Actuat. A Phys. 2011, 168, 253–261. DOI: 10.1016/j.sna.2011.04.007.

[18] Zhang, X.M.; Liu, A.Q.; Lu, C.; Tang, D.Y. A real pivot structure for MEMS tunable lasers. J. Microelectromech. Syst. 2007, 16, 269–278. DOI: 10.1109/JMEMS.2006.889532.

[19] Cai, H.; Liu, A.Q.; Zhang, X.M.; Tamil, J.; Tang, D.Y.; Zhang, Q.X.; Lu, C. A miniature tunable coupled-cavity laser constructed by micromachining technology. Appl. Phys. Lett. 2008, 92, 031105–031193. DOI: 10.1063/1.2831501.

[20] Wang, D.; Watkins, C.; Xie, H. MEMS mirrors for LiDAR: a review. Micromachines 2020, 11, 456. DOI: 10.3390/mi11050456.

[21] Holmstrom, S.T.S.; Baran, U.; Urey, H. MEMS laser scanners: a review. J. Microelectromech. Syst. 2014, 23, 259–275. DOI: 10.1109/JMEMS.2013.2295470.

[22] Ebermann, M.; Neumann, N.; Hiller, K.; Seifert, M.; Meinig, M.; Kurth, S. Tunable MEMS Fabry-Pérot filters for infrared microspectrometers: a review. MOEMS Miniaturized Syst. XV 2016, 9760, 97600H. DOI: 10.1117/12.2209288.

[23] Stännigl, K.; Rabl, P.; Sorensen, A.S.; Zoller, P.; Lukin, M.D. Optomechanical transducers for long-distance quantum communication. Phys. Rev. Lett. 2010, 105, 220501–220504. DOI: 10.1103/PhysRevLett.105.220501.

[24] Balram, K.C.; Davanço, M.I.; Song, J.D.; Srinivasan, K. Coherent coupling between radio frequency, optical, and acoustic waves in piezo-optomechanical circuits. Nat. Photonics. 2016, 10, 346–352. DOI: 10.1038/nphoton.2016.46.

[25] Dong, B.; Shi, Q.; Yang, Y.; Wen, F.; Zhang, Z.; Lee, C. Technology evolution from self-powered sensors to IoT enabled smart homes. Nano Energy 2021, 79, 105414. DOI: 10.1016/j.nanoen.2020.105414.

[26] Zhu, J.; Cho, M.; Li, Y.; He, T.; Ahn, J.; Park, J.; Ren, T.L.; Lee, C.; Park, I. Machine learning-enabled textile-based graphene gas sensing with energy harvesting-assisted IoT application. Nano Energy 2021, 86, 106035. DOI: 10.1016/j.nanoen.2021.106035.

[27] Haroun, A.F.; Le, X.; Gao, S.; Dong, B.; He, T.; Zhang, Z.; Wen, F.; Xu, S.; Lee, C. Progress in micro/nano sensors and nanoenergy for future IoT-based smart home applications. Nano Ex. 2021, 2, 022005. DOI: 10.1088/2632-959X/abf344.

[28] Wen, F.; He, T.; Liu, H.; Chen, H.-Y.; Zhang, T.; Lee, C. Advances in chemical sensing technology for enabling the next-generation self-sustainable integrated wearable system in the IoT era. Nano Energy 2020, 78, 105155. DOI: 10.1016/j.nanoen.2020.105155.

[29] Zhu, J.; Sun, Z.; Xu, J.; Walczak, R. D.; Dziuban, J. A.; Lee, C. Volatile organic compounds sensing based on Bennet Doubler-inspired triboelectric nanogenerator and machine learning-assisted ion mobility analysis. Sci. Bull. 2021, 66, 1176–1185. DOI: 10.1016/j.scib.2021.03.021.
Ma, Y.; Dong, B.; Wei, J.; Chang, Y.; Huang, L.; Ang, K.; Lee, C. High-responsivity mid-infrared black phosphorus slow light waveguide photodetector. Adv. Optical Mater. 2020, 8, 2000337. DOI: 10.1002/adom.202000337.

Dong, B.; Shi, Q.; He, T.; Zhu, S.; Zhang, Z.; Sun, Z.; Ma, Y.; Kwong, D. L.; Lee, C. Wearable triboelectric/aluminum nitride nano-energy-nano-system with self-sustainable photonic modulation and continuous force sensing. Adv Sci (Weinh.) 2020, 7, 1903636. DOI: 10.1002/advs.201903636.

Dong, B.; Yang, Y.; Shi, Q.; Xu, S.; Sun, Z.; Zhu, S.; Zhang, Z.; Kwong, D. L.; Zhou, G.; Ang, K. W.; Lee, C. Wearable Triboelectric-Human-Machine Interface (THMI) using robust nanophotonic readout. ACS Nano 2020, 14, 8915–8930. DOI: 10.1021/acsnano.0c03728.

Ma, Y.; Huang, Q.; Li, T.; Villanueva, J.; Nguyen, N. H.; Friend, J.; Sirbuly, D. J. A local nanofiber-optic ear. ACS Photonics 2016, 3, 1762–1767. DOI: 10.1021/acsp Photonics.6b00424.

Chang, Y.; Wei, J.; Lee, C. Metamaterials—from fundamentals and MEMS tuning mechanisms to applications. Nanophotonics 2020, 9, 3049–3070. DOI: 10.1515/nanoph-2020-0045.

Han, K.; Zhu, K.; Bahl, G. Opto-mechano-fluidic viscometer. Appl. Phys. Lett. 2014, 105, 014103. DOI: 10.1063/1.4887369.

Li, J. J.; Zhu, K. D. Nonlinear optical mass sensor with an optomechanical microresonator. Appl. Phys. Lett. 2012, 101, 141905. DOI: 10.1063/1.4757004.

Gomis-Bresco, J.; Navarro-Urrios, D.; Oudich, M.; El-Jallal, S.; Griol, A.; Puerto, D.; Chavez, E.; Pennec, Y.; Djafari-Rouhani, B.; Alzina, F.; et al. A one-dimensional optomechanical crystal with a complete photonic band gap. Nat. Commun. 2014, 5, 1–6. DOI: 10.1038/ncomms4552.

Oudich, M.; El-Jallal, S.; Pennec, Y.; Djafari-Rouhani, B.; Gomis-Bresco, J.; Navarro-Urrios, D.; Sotomayor Torres, C. M.; Martínez, A.; Makhoute, A. Optomechanic interaction in a corrugated photonic nanobeam cavity. Phys. Rev. B. 2014, 89, 245122. DOI: 10.1103/PhysRevB.89.245122.

Xia, J.; Qiao, Q.; Zhou, G.; Chau, S.; Zhou, G. Opto-mechanical photonic crystal cavities for sensing application. Applied Sciences 2020, 10, 7080. DOI: 10.3390/app10207080.

Aspelmeyer, M.; Kippenberg, T. J.; Marquardt, F. Cavity optomechanics. Rev. Mod. Phys. 2014, 86, 1391–1452. DOI: 10.1103/RevModPhys.86.1391.

Li, B.; Ho, C. P.; Lee, C. Tunable Butler-Townes splitting observation in coupled whispering gallery modes. IEEE Photonics J. 2016, 8, 1–10. DOI: 10.1109/JPHOT.2016.2601324.

Ho, C. P.; Pitchappa, P.; Kropelnicki, P.; Wang, J.; Cai, H.; Gu, Y.; Lee, C. Two-dimensional photonic-crystal-based Fabry-Perot etalon. Opt. Lett. 2015, 40, 2743–2746. DOI: 10.1364/ol.40.002743.

Ho, C. P.; Pitchappa, P.; Soon, B. W.; Lee, C. Suspended 2-D photonic crystal aluminum nitride membrane reflector. Opt. Express. 2015, 23, 10598–10603. DOI: 10.1364/oe.23.010598.

Ho, C. P.; Pitchappa, P.; Kropelnicki, P.; Wang, J.; Cai, H.; Gu, Y.; Lee, C. Characterization of polycrystalline silicon-based photonic crystal-suspended membrane for high temperature applications. J. Nanophoton. 2014, 8, 084096. DOI: 10.1117/1.JNP.8.084096.

Ho, C. P.; Pitchappa, P.; Kropelnicki, P.; Wang, J.; Gu, Y.; Lee, C. Development of polycrystalline silicon based photonic crystal membrane for mid-infrared applications. IEEE J. Sel. Top. Quantum Electron 2014, 20, 4900107. DOI: 10.1109/JSTQE.2013.2294463.

Lin, Y.-S.; Ho, C. P.; Koh, K. H.; Lee, C. Fabry-Perot filter using grating structures. Opt. Lett. 2013, 38, 902–904. DOI: 10.1364/ol.38.000902.

Krause, A. G.; Winger, M.; Blasius, T. D.; Lin, Q.; Painter, O. A high-resolution microchip optomechanical accelerometer. Nature Photon. 2012, 6, 768–772. DOI: 10.1038/nphoton.2012.245.

Chae, J.; An, S.; Ramer, G.; Stavila, V.; Holland, G.; Yoon, Y.; Talin, A. A.; Allendorf, M.; Aksyuk, V. A.; Centrone, A. Nanophotonic atomic force microscope transducers enable chemical composition and thermal conductivity measurements at the nanoscale. Nano Lett. 2017, 17, 5587–5594. DOI: 10.1021/acs.nanolett.7b02404.

Bekker, C.; Kalra, R.; Baker, C.; Bowen, W. P. Injection locking of an electro-optomechanical device. Optica 2017, 4, 1196. DOI: 10.1364/OPTICA.4.001196.

Han, X.; Fu, W.; Zhong, C.; Zou, C.-L.; Xu, Y.; Sayem, A. A.; Xu, M.; Wang, S.; Cheng, R.; Jiang, L.; Tang, H. X. Cavity Piezo-mechanics for superconducting-nanophotonic quantum interface. Nat. Commun. 2020, 11, 3237. DOI: 10.1038/s41467-020-17053-3.

Zhou, H.; Hui, X.; Li, D.; Hu, D.; Chen, X.; He, X.; Gao, L.; Huang, H.; Lee, C.; Mu, X. Metal–organic framework-surface-enhanced infrared absorption platform enables simultaneous on-chip sensing of greenhouse gases. Adv. Sci. 2020, 7, 2001173. DOI: 10.1002/advs.202001173.

Xu, J.; Ren, Z.; Dong, B.; Liu, X.; Wang, C.; Tian, Y.; Lee, C. Nanometer-scale heterogeneous interfacial Sapphire Wafer bonding for enabling plasmonic-enhanced nanofluidic mid-infrared spectroscopy. ACS Nano 2020, 14, 12159–12172. DOI: 10.1021/acsnano.0c05794.

McKeown, S. J.; Wang, X.; Yu, X.; Goddard, L. L. Realization of palladium-based optomechanical cantilever hydrogen sensor. Microsystems Nanoeng 2017, 3, 1–6. DOI: 10.1038/micronano.2016.87.
X. LIU ET AL.

[99] Metcalfe, M. Applications of cavity optomechanics. Appl. Phys. Rev. 2014, 1, 031105. DOI: 10.1063/1.4896029.

[100] Westerveld, W. J.; Leinders, S. M.; van Neer, P. L. M. J.; Urbach, H. P.; Jong, N. d.; Verweij, M. D.; Rottenberg, X.; Rochus, V. Optical micro-machined ultrasound sensors with a silicon photonic resonator in a buckled acoustical membrane. In 2019 20th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE); IEEE, Hannover, Germany, 2019; pp. 1–7. DOI: 10.1109/EuroSimE.2019.8724528.

[101] Niekiel, F.; Su, J.; Bodduluri, M. T.; Liseć, T.; Blöhm, L.; Pieper, I.; Wagner, B.; Lofink, F. Highly sensitive MEMS magnetic field sensors with integrated powder-based permanent magnets. Sens. Actuat. A Phys. 2019, 297, 111560. DOI: 10.1016/j.sna.2019.111560.

[102] Kim, K. H.; Luo, W.; Zhang, C.; Tian, C.; Jay Guo, L.; Wang, X.; Fan, X. Air-coupled ultrasound detection using capillary-based optical ring resonators. Sci. Rep. 2017, 7, 109. DOI: 10.1038/s41598-017-00134-7.

[103] Tu, T. W.; Wu, C. C.; Lee, P. T. 1D photonic crystal strain sensors. ACS Photonics 2018, 5, 2767–2772. DOI: 10.1021/acsphotonics.8b00560.

[104] Xiong, H.; Liu, Z.-X.; Wu, Y. Highly sensitive optical sensor for precision measurement of electrical charges based on optomechanically induced difference-sideband generation. Opt. Lett. 2017, 42, 3630–3633. DOI: 10.1364/ol.42.003630.

[105] Yao, M.; Zhang, Y.; Ouyang, X.; Ping Zhang, A.; Tam, H.-Y.; Wai, P. K. A. Ultracompact optical fiber acoustic sensors based on a fiber-top spirally-suspended optomechanical microresonator. Opt. Lett. 2020, 45, 3516–3519. DOI: 10.1364/ol.393900.

[106] Hutchison, D. N.; Bhave, S. A. Z-axis optomechanical accelerometer. In 2012 IEEE 25th International Conference on Micro Electro Mechanical Systems (MEMS); IEEE, Paris, France, 2012; pp. 615–619. DOI: 10.1109/MEMSYS.2012.6170263.

[107] Du, H.; Zhou, G.; Zhao, Y.; Chen, G.; Chau, F. S. Magnetic field sensor based on coupled photonic crystal nanobeam cavities. Appl. Phys. Lett. 2017, 110, 061110. DOI: 10.1063/1.4975804.

[108] Basiri-Esfahani, S.; Armin, A.; Forstner, S.; Bowen, W. P. Precision ultrasound sensing on a chip. Nat. Commun. 2019, 10, 132. DOI: 10.1038/s41467-018-08038-4.

[109] Winkler, A. M.; Maslov, K.; Wang, L. V. Noise-equivalent sensitivity of photoacoustics. J. Biomed. Opt. 2013, 18, 097003. DOI: 10.1117/1.JBO.18.9.097003.

[110] Wissmeyer, G.; Pleitez, M. A.; Rosenthal, A.; Ntziachrastos, V. Looking at sound: photoacoustics with all-optical ultrasound detection. Light. Sci. Appl. 2018, 7, 53. DOI: 10.1038/s41377-018-0036-7.

[111] Zhao, X.; Tsai, J. M.; Cai, H.; Ji, X. M.; Zhou, J.; Bao, M. H.; Huang, Y. P.; Kwong, D. L.; Liu, A. Q. A nano-opto-mechanical pressure sensor via ring resonator. Opt. Express. 2012, 20, 8535–8542. DOI: 10.1364/oe.20.008535.

[112] Liu, T.; Pagliano, F.; van Veldhoven, R.; Pogoretskiy, V.; Jiao, Y.; Fiore, A. Integrated nano-optomechanical displacement sensor with ultrawide optical bandwidth. Nat. Commun. 2020, 11, 2407. DOI: 10.1038/s41467-020-16269-7.

[113] Zeimpekis, I.; Sari, I.; Kraft, M. Characterization of a mechanical motion amplifier applied to a MEMS accelerometer. J. Microelectromech. Syst. 2012, 21, 1032–1042. DOI: 10.1109/JMEMS.2012.2196491.

[114] Mohammed, Z.; Dushaq, G.; Chatterjee, A.; Rasras, M. An optimization technique for performance improvement of gap-changeable MEMS accelerometers. Mechatronics 2018, 54, 203–216. DOI: 10.1016/j.mechatronics.2017.10.011.

[115] Ding, H.; Wu, C.; Xie, J. A MEMS resonant accelerometer with high relative sensitivity based on sensing scheme of electrostatically induced stiffness perturbation. J. Microelectromech. Syst. 2021, 30, 32–41. DOI: 10.1109/JMEMS.2020.3037838.

[116] Tian, B.; Liu, H.; Yang, N.; Zhao, Y.; Jiang, Z. Design of a piezoelectric accelerometer with high sensitivity and low transverse effect. Sensors 2016, 16, 1587. DOI: 10.3390/s16101587.

[117] Wang, Y.; Ding, H.; Le, X.; Wang, W.; Xie, J. A MEMS piezoelectric in-plane resonant accelerometer based on aluminum nitride with two-stage microleverage mechanism. Sens. Actuat. A Phys. 2017, 254, 126–133. DOI: 10.1016/j.sna.2016.12.019.

[118] Xu, M. h.; Zhou, H.; Zhu, L. h.; Shen, J. n.; Zeng, Y. b.; Feng, Y. j.; Guo, H. Design and fabrication of a D33-mode piezoelectric micro. Microsystems Technol. 2019, 25, 4465–4474. DOI: 10.1007/s00542-019-04495-z.

[119] Dong, B.; Cai, H.; Tsai, J. M.; Kwong, D. L.; Liu, A. Q. An on-chip opto-mechanical accelerometer. In 2013 IEEE 26th International Conference on Micro Electro Mechanical Systems (MEMS); IEEE, Hannover, Germany, 2013; pp. 641–644. DOI: 10.1109/MEMSYS.2013.6474323.

[120] Guzmán Cervantes, F.; Kumanchik, L.; Pratt, J.; Taylor, J. M. High sensitivity optomechanical reference accelerometer over 10 KHz. Appl. Phys. Lett. 2014, 104, 221111. DOI: 10.1063/1.4881936.

[121] Liu, F.; Alaie, S.; Leseman, Z. C.; Hossein-Zadeh, M. Sub-Pg mass sensing and measurement with an optomechanical oscillator. Opt. Express. 2013, 21, 19555–19567. DOI: 10.1364/OE.21.019555.
Huang, Y.; Flor Flores, J. G.; Li, Y.; Wang, W.; Wang, D.; Goldberg, N.; Zheng, J.; Yu, M.; Lu, M.; Kutzer, C.19; Guillen-Torres, M. A.; Almarghalani, M.; Sarraf, E. H.; Caverley, M.; Jaeger, N. A. F.; Cretu, E.; Christoski, L. Silicon photonics characterization platform for gyroscopic devices. In Photonics North 2014; MacLean, S., Plant, D. V., Eds.; 2014; Vol. 9288, p. 92880U. DOI: 10.1117/12.2075051.

Tsai, C. W.; Chen, K. H.; Shen, C. K.; Tsai, J. C. A MEMS doubly decoupled gyroscope with wide driving frequency range. IEEE Trans. Ind. Electron. 2012, 59, 4921–4929. DOI: 10.1109/TIE.2011.2177612.

Kim, P. H.; Hauer, B. D.; Doolin, C.; Souris, F.; Davis, J. P. Approaching the standard quantum limit of mechanical torque sensing. Nat. Commun. 2016, 7, 13165. DOI: 10.1038/ncomms13165.

Wu, M.; Wu, N. L. Y.; Firdous, T.; Fani Sani, F.; Losby, J. E.; Freeman, M. R.; Barclay, P. E. Nanocavity optomechanical torque magnetometer and radiofrequency susceptometry. Nat. Nanotechnol. 2017, 12, 127–131. DOI: 10.1038/nnano.2016.226.

Mao, H.; Ma, H.; Jin, Z. Polarization maintaining silica waveguide optic gyro using double phase modulation technique. Opt. Express. 2011, 19, 4632. DOI: 10.1364/OE.19.004632.

Mahmoud, A.; Mahmoud, M.; Mukherjee, T.; Piazza, G. Investigating the impact of resonant cavity design on surface acoustic wave gyroscopes. In In 2018 IEEE International Symposium on Inertial Sensors and Systems (INERTIAL); IEEE, Lake Como, Italy, 2018; pp. 1–4. DOI: 10.1109/ISISS.2018.8358137.

Chang, Y.; Xu, S.; Dong, B.; Wei, J.; Le, X.; Ma, Y.; Z, G.; Lu, M.; Kutzer, C.; et al. Development of triboelectric-enabled tunable Fabry Pérot photonic-crystal-slab filter towards wearable mid-infrared computational spectrometer. Nano Energy 2021, 89, 106446. accepted for publication. DOI: 10.1016/j.nanoen.2021.106446.

Kapfinger, S.; Reichert, T.; Lichtmannecker, S.; Müller, K.; Finley, J. J.; Wixforth, A.; Kaniber, M.; Krenner, H.J. Dynamic acousto-optic control of a strongly coupled photonic molecule. Nat. Commun. 2015, 6, 8540. DOI: 10.1038/ncomms9540.
[21] Hoffmann, J. M.; Yin, X.; Richter, J.; Hartung, A.; Maß, T. W. W.; Taubner, T. Low-cost infrared resonant structures for surface-enhanced infrared absorption spectroscopy in the fingerprint region from 3 to 13 μm. *J. Phys. Chem. C* **2013**, *117*, 11311–11316. DOI: 10.1021/jp402383h.

[22] Aouani, H.; Rahmani, M.; Šipová, H.; Torres, V.; Hegnerová, K.; Beruete, M.; Homola, J.; Hong, M.; Navarro-Cia, M.; Maier, S. A. Plasmonic nanoantennas for multispectral surface-enhanced spectroscopies. *J. Phys. Chem. C* **2013**, *117*, 18620–18626. DOI: 10.1021/jp404555x.

[23] Cetin, A. E.; Turkmen, M.; Aksu, S.; Etezadi, D.; Altug, H. Multi-resonant compact nanoaperture with accessible large nearfields. *Appl. Phys. B* **2015**, *118*, 29–38. DOI: 10.1007/s00340-014-5950-7.

[24] Gottheim, S.; Zhang, H.; Govorov, A. O.; Halas, N. J. Fractal nanoparticle plasmonics: the cayley tree. *ACS Nano* **2015**, *9*, 3284–3292. DOI: 10.1021/acsnano.5b00412.

[25] Aslan, E.; Aslan, E.; Wang, R.; Hong, M. K.; Erramilli, S.; Turkmen, M.; Saracoglu, O. G.; Dal Negro, L. Multispectral Cesaro-type fractal plasmonic nanoantennas. *ACS Photonics* **2016**, *3*, 2102–2111. DOI: 10.1021/acsphotonics.6b00540.

[26] Hasan, D.; Ho, C. P.; Lee, C. Realization of fractal-inspired thermoresponse Quasi-3D plasmonic metasurfaces with EOT-like transmission for volumetric and multispectral detection in the mid-IR region. *ACS Omega* **2016**, *1*, 818–831. DOI: 10.1021/acsomega.6b00201.

[27] Hasan, D.; Ho, C. P.; Pitchappa, P.; Yang, B.; Yang, C.; Lee, C. Thermoplasmonic study of a triple band optical nanoantenna strongly coupled to midIR molecular mode. *Sci. Rep.* **2016**, *6*, 22227. DOI: 10.1038/srep22227.

[28] Ren, Z.; Dang, Z.; Lee, C. Multi-band mid-IR molecules identification using plasmonic metamaterials induced by bright-dark coupling. In 2020 *IEEE 33rd International Conference on Micro Electro Mechanical Systems (MEMS)*; IEEE, Vancouver, BC, Canada, 2020; January, 2020; pp 725–728. DOI: 10.1109/MEMS4641.2020.9056326.

[29] Maß, T. W. W.; Taubner, T. Incident angle-tuning of infrared antenna array resonances for molecular sensing. *ACS Photonics* **2015**, *2*, 1498–1504. DOI: 10.1021/acsphotonics.5b00399.

[30] Leitis, A.; Tittl, A.; Liu, M.; Lee, B. H.; Gu, M. B.; Kivshar, Y. S.; Altug, H. Angle-multiplexed all-dielectric metasurfaces for broadband molecular fingerprint retrieval. *Sci. Adv.* **2019**, *5*, eaaw2871. DOI: 10.1126/sciadv.aaw2871.

[31] Chen, N.; Pitchappa, P.; Ho, C. P.; Hasan, D.; Kropelnicki, P.; Alioto, M.; Lee, C. Polarization controllable multispectral symmetry-breaking absorberin mid-infrared. *J. Appl. Phys.* **2016**, *120*, 063105. DOI: 10.1063/1.4960347.

[32] Pitchappa, P.; Kumar, A.; Prakash, S.; Jani, H.; Venkatesan, T.; Singh, R. Chalcogenide phase change material for active terahertz photonics. *Adv. Mater.* **2019**, *31*, 1808157. DOI: 10.1002/adma.201808157.

[33] Rudé, M.; Mkhitaryan, V.; Cetin, A. E.; Miller, T. A.; Carrilero, A.; Wall, S.; de Abajo, F. J. G.; Altug, H.; Pruneri, V. Ultrafast and broadband tuning of resonant optical nanostructures using phase-change materials. *Adv. Opt. Mater.* **2016**, *4*, 1060–1066. DOI: 10.1002/adom.201600079.

[34] Rodrigo, D.; Tittl, A.; Limaj, O.; De Abajo, F. J. G.; Pruneri, V.; Altug, H. Double-layer graphene for enhanced tunable infrared plasmonics. *Light Sci. Appl.* **2017**, *6*, 16277–16277. DOI: 10.1038/lsa.2016.277.

[35] Hu, H.; Yang, X.; Guo, X.; Khaliji, K.; Biswas, S. R.; García de Abajo, F. J.; Low, T.; Sun, Z.; Dai, Q. Gas identification with graphene plasmons. *Nat. Commun.* **2019**, *10*, 1131. DOI: 10.1038/s41467-019-09008-0.

[36] Zhu, Y.; Li, Z.; Hao, Z.; DiMarco, C.; Maturavaongsadit, P.; Hao, Y.; Lu, M.; Stein, A.; Wang, Q.; Hone, J.; et al. Optical conductivity-based ultrasensitive mid-infrared biosensing on a hybrid metasurface. *Light. Sci. Appl.* **2018**, *7*, 67. DOI: 10.1038/s41377-018-0066-1.

[37] Li, Z.; Zhu, Y.; Hao, Y.; Gao, M.; Lu, M.; Stein, A.; Park, A.-H. A.; Hone, J. C.; Lin, Q.; Yu, N. Hybrid metasurface-based mid-infrared biosensor for simultaneous quantification and identification of monolayer protein. *ACS Photonics* **2019**, *6*, 501–509. DOI: 10.1021/acsphotonics.8b01470.

[38] Chen, N.; Hasan, D.; Ho, C. P.; Lee, C. Graphene tunable plasmon–phonon coupling in Mid-IR complementary metamaterial. *Adv. Mater. Technol.* **2018**, *3*, 1800014. DOI: 10.1002/admt.201800014.

[39] Pitchappa, P.; Pei Ho, C.; Kropelnicki, P.; Singh, N.; Kwong, D.-L.; Lee, C. Micro-electro-mechanically switchable near infrared complementary metamaterial absorber. *Appl. Phys. Lett.* **2014**, *104*, 201114. DOI: 10.1063/1.4879284.

[40] Ma, F.; Lin, Y.-S.; Zhang, X.; Lee, C. Tunable multiband terahertz metamaterials using a reconfigurable electric split-ring resonator array. *Light Sci. Appl.* **2014**, *3*, e171–e171. DOI: 10.1038/lsa.2014.52.

[41] Dong, B.; Ma, Y.; Ren, Z.; Lee, C. Recent progress in nanoplasmonics-based integrated optical micro/nano-systems. *J. Phys. D: Appl. Phys.* **2020**, *53*, 213001. DOI: 10.1088/1361-6463/ab77db.

[42] Ren, Z.; Chang, Y.; Ma, Y.; Shih, K.; Dong, B.; Lee, C. Leveraging of MEMS technologies for optical metamaterials applications. *Adv. Optical Mater.* **2020**, *8*, 1900653. DOI: 10.1002/adom.201900653.

[43] Zhu, J.; Ren, Z.; Lee, C. Toward healthcare diagnoses by machine-learning-enabled volatile organic compound identification. *ACS Nano* **2021**, *15*, 894–903. DOI: 10.1021/acs.nano.0c07464.
[234] Vincent, T. A.; Gardner, J. W. A low cost MEMS based NDIR system for the monitoring of carbon dioxide in breath analysis at Ppm levels. Sens. Actuat. B Chem. 2016, 236, 954–964. DOI: 10.1016/j.snb.2016.04.016.

[235] Wang, H.; Wu, H.; Hasan, D.; He, T.; Shi, Q.; Lee, C. Self-powered dual-mode amenity sensor based on the water-air triboelectric nanogenerator. ACS Nano. 2017, 11, 10337–10346. DOI: 10.1021/acsnano.7b05213.

[236] Moumen, S.; Raible, I.; Krauß, A.; Wöllenstein, J. Infrared investigation of CO2 sorption by amine based materials for the development of a NDIR CO2 sensor. Sens. Actuat. B Chem. 2016, 236, 1083–1090. DOI: 10.1016/j.snb.2016.06.014.

[237] Hasan, D.; Lee, C. Hybrid metamaterial absorber platform for sensing of CO2 gas at mid-IR. Adv. Sci. 2018, 5, 1700581. DOI: 10.1002/advs.201705851.

[238] Hasan, D.; Pitchappa, P.; Wang, J.; Wang, T.; Yang, H.; Ho, C. P.; Lee, C. Novel CMOS-compatible Mo–AlN–Mo platform for metamaterial-based mid-IR absorber. ACS Photonics 2017, 4, 302–315. DOI: 10.1021/acsphotonics.6b00672.

[239] Hasan, D.; Pitchappa, P.; Pei Ho, C.; Lee, C. High temperature coupling of IR inactive CC mode in complementary metal oxide semiconductor metasurface. Adv. Opt. Mater. 2017, 5, 1600778. DOI: 10.1002/adom.201600778.

[240] Chang, Y.; Hasan, D.; Dong, B.; Wei, J.; Ma, Y.; Zhou, G.; Lee, C. All-dielectric surface-enhanced infrared absorption-based gas sensor using guided resonance. ACS Appl Mater Interfaces 2018, 10, 38272–38279. DOI: 10.1021/acsami.8b16623.

[241] Singhal, A. V.; Charaya, H.; Lahiri, I. Noble metal decorated graphene-based gas sensors and their fabrication: a review. Crit. Rev. Solid State Mater. Sci. 2017, 42, 499–526. DOI: 10.1080/10408436.2016.1244656.

[242] Lee, I.; Martin-Moreno, L.; Mohr, D. A.; Khalaji, K.; Low, T.; Oh, S. Anisotropic acoustic plasmons in black phosphorus. ACS Photonics 2018, 5, 2208–2216. DOI: 10.1021/acsphotonics.8b00062.

[243] Cui, S.; Pu, H.; Wells, S. A.; Wen, Z.; Mao, S.; Chang, J.; Hersam, M. C.; Chen, J. Ultrahigh sensitivity and layer-dependent sensing performance of phosphorene-based gas sensors. Nat. Commun. 2015, 6, 8632. DOI: 10.1038/ncomms9632.

[244] Kou, L.; Frauenheim, T.; Chen, C. Phosphorene as a superior gas sensor: selective adsorption and distinct I–V response. J. Phys. Chem. Lett. 2014, 5, 2675–2681. DOI: 10.1021/jz501188k.

[245] Pham, T.; Li, G.; Bekyarova, E.; Itkis, M. E.; Mulchandani, A. MoS2 -based optoelectronic gas sensor with sub-parts-per-billion limit of NO2 gas detection. ACS Nano 2019, 13, 3196–3205. DOI: 10.1021/acsnano.8b08778.

[246] Shokri, A.; Salami, N. Gas sensor based on MoS2 monolayer. Sens. Actuat. B Chem. 2016, 236, 378–385. DOI: 10.1016/j.snb.2016.06.033.

[247] Lee, I.-H.; Yoo, D.; Avouris, P.; Low, T.; Oh, S.-H. Graphene acoustic plasmon resonator for ultrasensitive infrared spectroscopy. Nat. Nanotechnol. 2019, 14, 313–319. DOI: 10.1038/s41565-019-0363-8.

[248] Bai, Y.; Zhang, D.; Lan, L.; Huang, Y.; Maize, K.; Shakouri, A.; Cheng, J.-X. Ultrafast chemical imaging by widefield photothermal sensing of infrared absorption. Sci. Adv. 2019, 5, eaav7127. DOI: 10.1126/sciadv.aav7127.

[249] Zhang, D.; Lan, L.; Bai, Y.; Majeeed, H.; Kandel, M. E.; Popescu, G.; Cheng, J.-X. Bond-selective transient phase imaging via sensing of the infrared photothermal effect. Light. Sci. Appl. 2019, 8, 116. DOI: 10.1038/s41377-019-0224-0.

[250] Barella, M.; Violi, I. L.; Gargiulo, J.; Martinez, L. P.; Goschin, F.; Guglielmotti, V.; Pallarola, D.; Schlücker, S.; Pilo-Pais, M.; Acuna, G. P.; et al. In situ photothermal response of single gold nanoparticles through hyperspectral imaging anti-stokes thermometry. ACS Nano. 2021, 15, 2458–2467. DOI: 10.1021/acs.nano.0c06185.

[251] Qiu, G.; Gai, Z.; Tao, Y.; Schmitt, J.; Kullak-Ublick, G. A.; Wang, J. Dual-functional plasmonic photothermal biosensors for highly accurate severe acute respiratory syndrome coronavirus 2 detection. ACS Nano. 2020, 14, 5268–5277. DOI: 10.1021/acsnano.0c02439.

[252] Wei, J.; Lee, C. Anomalous plasmon hybridization in nanoantennas near interfaces. Opt. Lett. 2019, 44, 6041–6044. DOI: 10.1364/OL.44.006041.

[253] Sun, F.; Wei, J.; Dong, B.; Ma, Y.; Chang, Y.; Tian, H.; Lee, C. Coexistence of air and dielectric modes in single nanocavity. Opt. Express. 2019, 27, 14085–14098. DOI: 10.1364/oe.27.014085.

[254] Liu, Y.; Liang, B.; Zhang, X.; Hu, N.; Li, K.; Chiavalioli, F.; Gui, X.; Guo, T. Plasmonic fiber-optic photothermal anemometers with carbon nanotube coatings. J. Lightwave Technol. 2019, 37, 3373–3380. DOI: 10.1109/JLT.2019.2916572.

[255] Wang, Y.; Gan, X.; Zhao, C.; Fang, L.; Mao, D.; Xu, Y.; Zhang, F.; Xi, T.; Ren, L.; Zhao, J. All-optical control of microfiber resonator by graphene's photothermal effect. Appl. Phys. Lett. 2016, 108, 171905. DOI: 10.1063/1.4947577.
[256] Breitegger, P.; Lang, B.; Bergmann, A. Intensity modulated photothermal measurements of NO₂ with a compact fiber-coupled Fabry–Pérot interferometer. *Sensors* 2019, 19, 3341. DOI: 10.3390/s19153341.

[257] Heylman, K. D.; Thakkar, N.; Horak, E. H.; Quillin, S. C.; Cherqui, C.; Knapper, K. A.; Masiello, D. J.; Goldsmith, R. H. Optical microresonators as single-particle absorption spectrometers. *Nature Photon.* 2016, 10, 788–795. DOI: 10.1038/nphoton.2016.217.

[258] Guha, B.; Lipson, M. Controlling thermo-optic response in microresonators using bimaterial cantilevers. *Opt. Lett.* 2015, 40, 103–106. DOI: 10.1364/OL.40.000103.

[259] Vasiliev, A.; Malik, A.; Muneeb, M.; Kuyken, B.; Baets, R.; Roelkens, G. On-chip mid-infrared photothermal spectroscopy using suspended silicon-on-insulator microring resonators. *ACS Sens.* 2016, 1, 1301–1307. DOI: 10.1021/acssensors.6b00428.

[260] Pruessner, M. W.; Park, D.; Stievater, T. H.; Kozak, D. A.; Rabinovich, W. S. Optomechanical cavities for all-optical photothermal sensing. *ACS Photonics* 2018, 5, 3214–3221. DOI: 10.1021/acsphotonics.8b00452.

[261] Zhao, Q.; Khan, M. W.; Farzinazar, S.; Lee, J.; Boyraz, O. Plasmo-thermomechanical radiation detector with on-chip optical readout. *Opt. Express.* 2018, 26, 29638–29650. DOI: 10.1364/OE.26.029638.

[262] Yu, H.; Wang, H.; Xiong, Q.; Mei, J.; Zhang, Y.; Wang, Y.; Lai, J.; Chen, C. Photothermal switch of sub-microsecond response: a monolithic-integrated ring resonator and a metasurface absorber in silicon photonic crystals. *Opt. Lett.* 2020, 45, 1806. DOI: 10.1364/OL.383959.

[263] Zuo, Y.; Gao, Y.; Qin, S.; Wang, Z.; Zhou, D.; Li, Z.; Yu, Y.; Shao, M.; Zhang, X. Broadband multi-wavelength optical sensing based on photothermal effect of 2D MXene films. *Nanophotonics* 2019, 9, 123–131. DOI: 10.1515/nanoph-2019-0338.

[264] Watts, M. R.; Shaw, M. J.; Nielson, G. N. Microphotonic thermal imaging. *Nat. Photon.* 2007, 1, 632–634. DOI: 10.1038/nphoton.2007.219.

[265] Zhang, C.; Giroux, M.; Nour, T. A.; St-Gelais, R. Thermal radiation sensing using high mechanical Q-factor silicon nitride membranes. In *2019 IEEE Sensors;* IEEE, Montreal, QC, Canada, 2019; Oct 2019; pp. 1–4. DOI: 10.1109/SENSORS43011.2019.8956551.

[266] Zhao, Q.; Sadri-Moshkenani, P.; Khan, M. W.; Torun, R.; Boyraz, O. On-chip bimetallic plasmo-thermomechanical detectors for mid-infrared radiation. *IEEE Photon. Technol. Lett.* 2017, 29, 1459–1462. DOI: 10.1109/LPT.2017.2728373.

[267] Shi, Q.; Dong, B.; He, T.; Sun, Z.; Zhu, J.; Zhang, Z.; Lee, C. Progress in wearable electronics/photonics—moving toward the era of artificial intelligence and internet of things. *InfoMat* 2020, 2, 1131–1162. DOI: 10.1002/inf2.12122.