Journal of Applied Physics

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Cite as: J. Appl. Phys. **128**, 240901 (2020); https://doi.org/10.1063/5.0033056
Submitted: 13 October 2020 . Accepted: 03 December 2020 . Published Online: 22 December 2020

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Journal of Applied Physics PERSPECTIVE scitation.org/journal/jap

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Cite as: J. Appl. Phys. **128**, 240901 (2020); doi: 10.1063/5.0033056
Submitted: 13 October 2020 · Accepted: 3 December 2020 ·
Published Online: 22 December 2020

View Online Export Citation CrossMark

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ABSTRACT

The miniaturization of infrared spectroscopy enables portable and low-cost devices, which could revolutionize many scientific and technological fields including environment monitoring, pharmacy, and biosensing. As a promising approach, metamaterial technologies have been widely developed in miniaturizing all the individual components of infrared spectroscopy such as light sources, sensors, spectral filters, and photodetectors. However, a systematic consideration on the whole device level is still lacking. In this Perspective, we focus on the possible opportunities offered by metamaterials for ultracompact infrared spectroscopy. To start with, we review the recent metamaterial-related component-level demonstrations. Then, we draw attention to the potential role of metamaterials as a common platform for all the individual components. Finally, we discuss about the near field effect in metamaterial-mediated devices.

I. INTRODUCTION

Infrared spectroscopy is of critical importance for many scientific and technological advances, including environment monitoring, pharmacy, chemical analysis, and biosensing.[1–3] The major uniqueness of this technology lies in its ability to detect the rich information on the light–matter interaction in the infrared range, also known as the absorption "fingerprint" of molecules.[4] The absorption spectra of molecules are directly linked to their constituents, chemical bonds, and configuration.[5] Consequently, infrared spectroscopy enables us to detect the analytes remotely, label-free, and selectively, which is advantageous over other methods.[6–10] The implementation of the infrared spectroscopy requires four essential components: light source, sensing part, spectral filter, and photodetector. In conventional devices, e.g., non-dispersive infrared spectroscopy (NDIR),[11,12] the components are bulky and lacking a common fabrication platform, and hence the total device suffers a large volume, as shown in Fig. 1(a). The bulky volume will inevitably hinder the practical application of infrared spectroscopy.

The miniaturization of infrared spectroscopy is hence highly desired for its ability to revolutionize this field by offering new possibilities for a variety of applications such as the Internet of Things (IoT), sensor networks, and wearable and point-of-care systems.[13] To miniaturize infrared spectroscopy, the size of every component should be scaled down, while the performance should remain to obtain an acceptable overall sensitivity. Unfortunately, the size-performance trade-off is usually difficult to overcome. For example, the Beer–Lambert law,[14] saying that the absorption of substances decreases exponentially with the light–matter interaction length, potentially imposes a limit on the detectivity of miniaturized devices. One alternative could be the on-chip approach, where optical waveguides are compactly winded on a single chip, allowing for the sensitive detection of molecules.[15–20] However, a mature platform for mid-infrared waveguide sensors, including the integration of light source, waveguide, filters, and detectors, is still not available. Especially, waveguide-integrated mid-infrared light sources and detectors are still in their early stage.

Metamaterials, featuring strong field localization and rich functionalities, offer unique opportunities for miniaturized

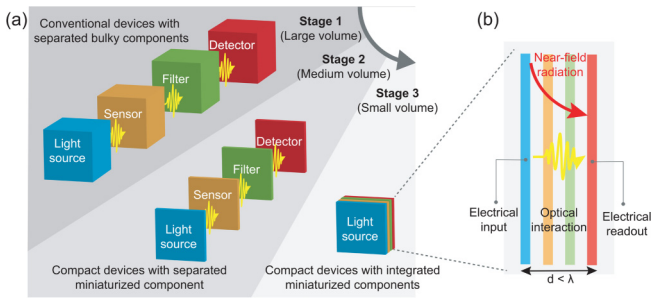

FIG. 1. Development path of miniaturized infrared spectroscopy. (a) Three stages of the development of infrared spectroscopy. (b) Exploded view of the ultracompact device with miniaturized integrated components. Near-field radiation will play a role when the dimension of device is approaching the wavelength of light.

infrared spectroscopy.[21,22] As artificial materials with engineered structures, metamaterials can be used to design photonic cavities supporting high Q-factor and large field enhancement, in which light is trapped for a long time for boosted light–matter interaction.[23–26] Besides, the design freedom endowed by metamaterials allows intriguing optical component response, such as polarization dependence, wavelength selectivity, and even handedness.[27,28] Importantly, recent studies have shown that metamaterials can be compatible with the modern CMOS process, making the future price low.[29–31] In the past decade, we have seen many exciting works using metamaterials for component-level demonstrations, including all the components of infrared spectroscopy, as illustrated by stage 2 in Fig. 1(a).[31–34] However, a systematic consideration on the whole device level is still lacking.

In this Perspective, we will focus on the opportunities and challenges offered by metamaterial infrared spectroscopy. By reviewing the recent progress in metamaterial-based miniaturized infrared sensors, we would like to draw special attention to two outstanding advantages of this approach. First, metamaterials bring the performance enhancement and more functionalities which relaxes the restrictions in material selection so that different components may be fabricated through similar processes. Second, this approach is promising to thin down the components to the wavelength of infrared, e.g., several micrometers, while the performance is maintained or even increased due to the contribution of near-field radiation. The above two merits would open exciting possibilities for miniaturized or super-compact infrared spectroscopy, as illustrated in stage 3 in Figs. 1(a) and 1(b).

II. METAMATERIAL-MEDIATED LIGHT SOURCE

Light sources with a wide wavelength coverage and sufficient power are the prerequisite of infrared spectroscopy. Miniaturized light sources, e.g., nanolasers, have attracted much attention in the recent years.[35,36] In these works, engineered structures play a key role. In this section, we review the recent metamaterial-based light sources. As shown in Fig. 2, these works can be divided into four quadrants of a Cartesian coordinate system based on their coherence degree and configuration, namely, (a) out-of-plane lasers, (b) in-plane lasers, (c) out-of-plane thermal emitters, and (d) in-plane thermal emitters. Briefly speaking, out-of-plane and in-plane are two main configurations that the next-generation infrared spectroscopy may adopt. Lasers and thermal radiators are two types of distinct light sources that hold respective advantages and disadvantages. In the following, we will discuss the four scenarios in more detail.

A. Metamaterial assisted out-of-plane lasers

To implement a laser, three essential parts are required, i.e., pump, active medium, and optical resonator.[37] Conventionally, the optical resonators are formed by two mirrors which are inherently bulky. To miniaturize this component, metamaterials can be used, which allows us to design cavities in sub-wavelength scales. In the past few years, a variety of engineered structures have been reported to design novel lasers with low lasing threshold, small dimension, fast speed, unique functions, and improved performance. For example, the good optical confinement of photonic crystal cavity allows itself to be integrated with various gain media for efficient lasing.[38–42] As shown in Fig. 2(a), Wu *et al.* reported a combination of atomic thin semiconductors and photonic crystal cavities, achieving a visible laser with a low threshold power of only 27 nW at 130 K.[32] The design flexibility of metamaterials also allows the implementation of novel physical concepts, such as bound states in the continuum (BIC), for lasing applications.[43] The emission wavelength and the threshold power of the BIC laser can be conveniently tuned by geometrically tailoring the structures. Strikingly, the lasing can even exist in a device within 10 μm. In another work, directional lasing was demonstrated in resonant semiconductor nanoantenna arrays by breaking a bound state in the continuum (quality factor, $Q \sim 2750$).[44] Again, the lasing directivity and wavelength can be tuned via the geometry of nanoantennas, which is unusual in traditional lasers. In addition to the great interest in scientific research, engineered nanocubes have been reported to largely increase the stability of the emission efficiency of organic light-emitting devices (OLEDs), while keeping the emission efficiency high, which is extremely desired for commercial applications.[45] The out-of-plane lasers are suitable for the integration with other components in a layer-by-layer configuration, which could be the most promising light sources that are used in miniaturized infrared spectroscopy.

B. Metamaterial assisted in-plane lasers

While the metamaterial assisted out-of-plane laser is a straightforward way to miniaturize the conventional bulky devices, there exists another approach of lasing where all components are integrated on a single chip via standard fabrication processes.[17,46–49] In this scenario, light sources that are directly coupled to waveguide should be designed. Although the physics of these designs is similar to that of out-of-plane devices, the implementation of in-plane lasers is usually more challenging, in which mode coupling needs to be carefully considered. A well designed in-plane laser should be dark to the free space mode, or the continuum, but weakly leaky to the waveguide mode. As shown in Fig. 2(b), Yu *et al.* demonstrated a waveguide-integrated self-pulsing laser via coupling the continuum of waveguide modes and

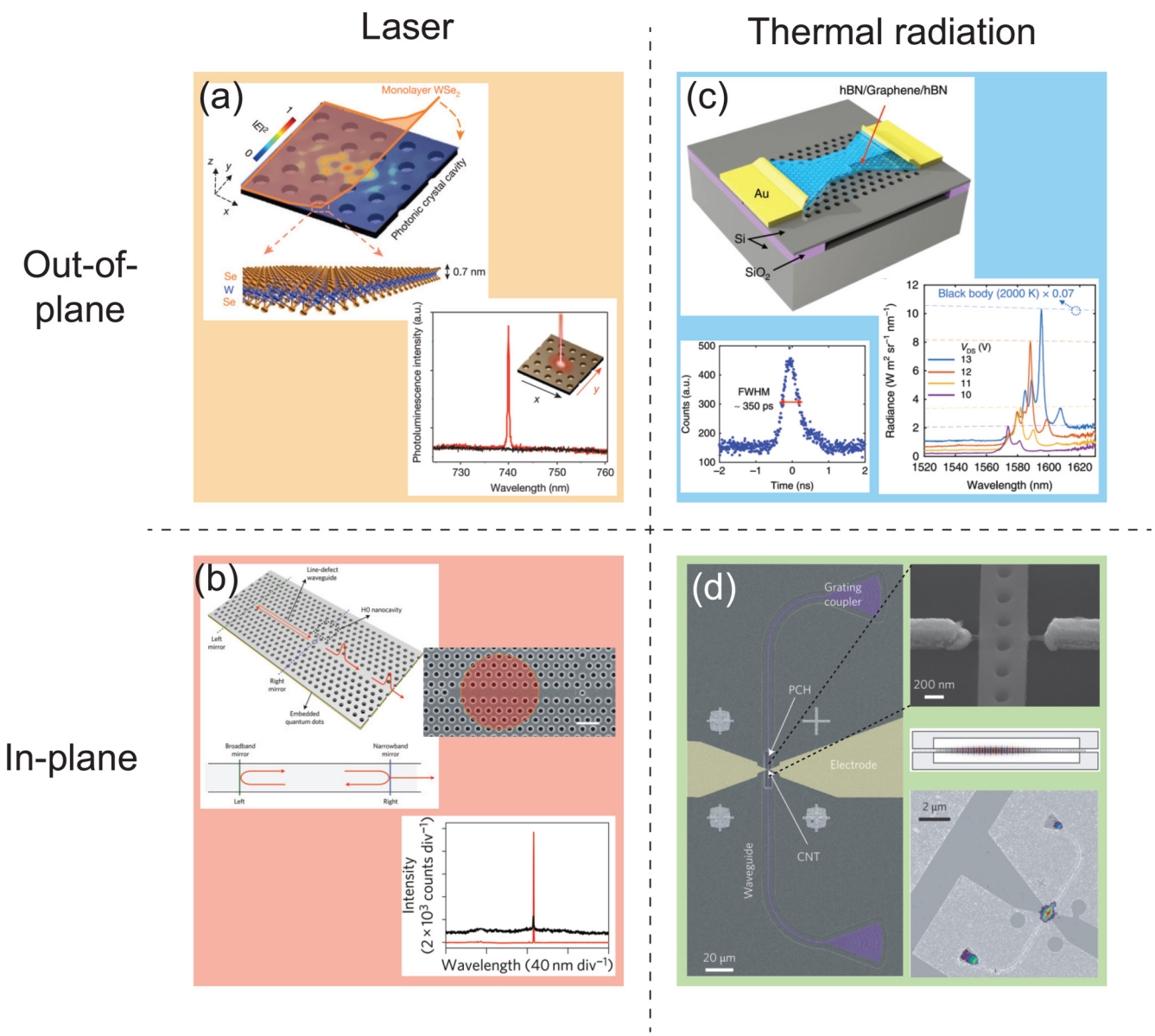

FIG. 2. Metamaterials for compact light sources. Based on the coherence degree, the light sources can be divided into laser (a) and (b) and thermal radiation (c) and (d). Based on the configuration, they can also be sorted into out-of-plane (a) and (c) and in-plane (b) and (d) devices. The role of metamaterials here is to form optical cavities with large field enhancement and increased density of states which are generally advantageous for efficient light generation. [(a) Reproduced with permission from Wu *et al.*, Nature **520**, 69–72 (2015). Copyright 2015 Springer Nature; (b) Reproduced with permission from Yu *et al.*, Nat. Photon. **11**, 81–84 (2017). Copyright 2016 Springer Nature; (c) Reproduced with permission from Shiue *et al.*, Nat. Commun. **10**, 109 (2019). Copyright 2019 Springer Nature; (d) Reproduced with permission from Pyatkov *et al.*, Nat. Photonics **10**, 420–427 (2016). Copyright 2016 Springer Nature.]

discrete nanocavity mode via Fano interference, which also allows the modulation of the laser via geometric tuning.[50] In this structure, the cavity and the waveguide are separated by a hole defect which acts as the mirror of laser cavity. Due to the property of Fano resonance and the nonlinearity of materials, lasing from such cavities becomes pulse-like although the pumping is continuous. For the final targets such as on-chip interconnects or sensing applications, the lasers are preferred to be electrically pumped rather than optically pumped. In 2017, Crosnier *et al.* reported an ultra-compact laser diode via a hybrid integration of InP nanoribs and

silicon waveguides.[36] In this design, carriers can be efficiently injected without hampering its optical properties. The demonstrated emission efficiency is as large as 10%, with a low current threshold of 100 μA. Compared to the out-of-plane configuration, the in-plane lasers are advantageous in terms of smaller footprint, free of coupling loss, and compatibility with commercial fabrication processes. The above examples show that metamaterials, or engineered nanostructures, also play a key role in the in-plane lasers.

C. Metamaterial assisted out-of-plane thermal emitters

Thermal emitters, e.g., incandescent lamps, are the most widely used light sources due to their simple design and low cost.[51–53] However, these conventional light sources face two intrinsic problems, namely, low emission power and lack of functionalities. Above absolute zero kelvin temperature, all objects radiate energy as described by the Stefan–Boltzmann law,[54,55]

$$P = \varepsilon \frac{2\pi^5 k^4}{15c^2h^3} T^4, \tag{1}$$

where ε is the emissivity, k is the Boltzmann constant, h is Planck's constant, c is the speed of light in vacuum, and T is the temperature. From Eq. (1), we can see that the overall emission power can only be increased via higher temperatures or larger emissivity, which become challenging when the device is small. For example, according to the Kirchhoff's law of thermal radiation, the emissivity of a thermal emitter is equal to its absorptivity. As the size of emitter becomes small as required in miniaturized infrared spectroscopy, the overall absorption of thermal emitters may drop significantly, which, in turn, leads to lower emission power. Besides, the high temperature (>1000 K) of thermal emitters puts more challenges in the integration with other components. In addition, conventional thermal emitters generally lack functionalities, such as spectral selectivity, polarization dependence, spatial and temporal modulation, which also impedes its applications in the emerging novel devices.[56–61] To address the above two issues, we have seen many works reported on metamaterial assisted thermal emitters in the past few years. For example, Ilic *et al.* reported demonstration of incandescent tungsten filaments surrounded by a cold photonic crystal slab, which avoids the waste of energy in undesired wavelength ranges, leading to strikingly high luminous efficiencies of about 40%.[62] The core design concept of this work is to tailor the radiation spectra of thermal emitters. In addition, the metamaterials control the emissivity and hence allows much faster modulation of thermal radiation. In 2017, Liu *et al.* reported a reconfigurable infrared emitter via microelectromechanical system (MEMS) based metamaterials.[63] The demonstrated devices can work up to 110 kHz, which is much faster than the conventional emitters limited by thermal constant. In addition to MEMS technology, phase change materials, e.g., GST, can also be applied to implement tunable thermal emitters which may offer faster working speed.[64] Recently, Xiao *et al.* reported a record-high modulation speed of thermal emission in the nanosecond range.[65] These modulated thermal emission can be useful in sensing applications, since working at high frequencies could largely get rid of the environment noises. When the components of infrared spectroscopy are closely packed as desired, the high temperature of thermal emitters may be a problem. This may be circumvented by leveraging the radiation from hot carriers. As shown in Fig. 2(c), due to the weak electron–phonon coupling in graphene, the temperature of electron can be raised by current bias, but the temperature of lattice is still relatively cool.[66] The photonic crystal is again used here to enhance the emission of hot electrons. The metamaterial-enhanced thermal emission from hot carriers is highly interesting for compact infrared spectroscopy.

D. Metamaterial assisted in-plane thermal emitters

An even more challenging design for thermal emitters is to directly integrate them with a waveguide. At first glance, one may naïvely think that there is not much difference in coupling light to waveguide between with a laser or thermal emitters. In fact, however, the latter case is much more difficult because of the incoherent nature of thermal emitters. Due to the incoherent nature of thermal emission, the maximum power radiated by a blackbody is only limited by its area and temperature. Similarly, there are theoretical works reporting that there also exists a limitation for the maximum thermal radiation power into a waveguide, which is only dependent on the number of modes and temperature.[67] Considering the small cross section of waveguides in most applications, the allowed power transmitted through a single waveguide is only 470 nW for a heater temperature of 1000 K. Therefore, if thermal emitters are to be used for waveguides, the design of other parts should be very careful to avoid further decrease in performance, such as heat loss, coupling loss, scattering loss, and noises in photodetectors. As shown in Fig. 2(d), Pyatkov *et al.* demonstrated a cavity enhanced thermal radiation from a biased carbon nanotube.[68] The enhancement is due to the largely increased optical density of states in the photonic crystal cavity. The emission can be tuned in spectra and time, which are suitable for power-efficient on-chip active light sources. However, the low available power of this approach may limit its practical application in infrared spectroscopy.[20]

III. METAMATERIAL-MEDIATED SENSORS

Apart from light sources, metamaterials also play a key role in the sensing elements, where the absorption signals of molecules can be enhanced via strong light–matter interaction.[69] Conventionally, due to the dimension mismatch between infrared wavelength and molecules, the intrinsic absorption of molecules is usually very weak. Following Beer's law, long interaction length is a must in conventional devices to achieve large absorption, making the overall device bulky. As a promising solution, metamaterial assisted surface enhanced infrared absorption spectroscopy (SEIRA) can boost the absorption of molecules by even several orders, while keeping the device size small.[70–72] To fully understand the role of nanostructures in such designs, the system can be modeled with the temporal coupled mode theory.[73–76] For example, the equations for a general two-port system, e.g., with transmission and reflection, can be written as (model shown in Fig. 3 center)[76]

$$\frac{d}{dt}P = j\omega_0 P - (\gamma_r + \gamma_a)P + j\mu M + \sqrt{\gamma_r}s_{in}, \tag{2}$$

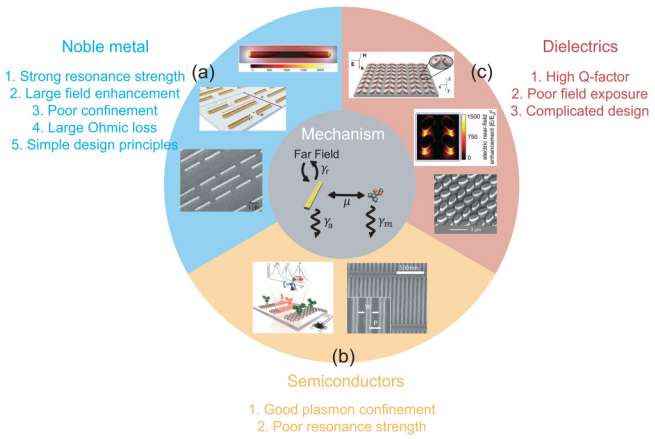

FIG. 3. Metamaterials for compact sensors. With the large localized field of metamaterial, the vibration of molecules at its vicinity can be strongly enhanced via the mutual coupling between plasmonic resonators and molecules. The mechanism of metamaterial sensors can be captured with the temporal coupled mode theory. γ_r and γ_a represent the radiative and absorptive damping of plasmonic resonators, respectively. γ_m is the absorptive damping of molecules. μ denotes the mutual coupling strength. With different design principles, three main types of materials are used for metamaterial sensors, namely, noble metals, semiconductors, and dielectrics. [(Center) Adapted with permission from Wei *et al.*, ACS Appl. Mater. Interfaces **11**(50), 47270–47278 (2019). Copyright 2019 American Chemical Society; (a) Reproduced with permission from Pyatkov *et al.*, Phys. Rev. Lett. **10**, 420–427 (2016). Copyright 2016 American Physical Society; Reproduced with permission from Rodrigo *et al.*, Nat. Commun. **9**, 2160 (2018). Copyright 2018 Springer Nature; (b) Rodrigo *et al.*, Science **349**, 165–168 (2015). Copyright 2015 American Association for the Advancement of Science; (c) Koshelev *et al.*, Phys. Rev. Lett. **121**, 193903 (2018). Copyright 2018 American Physical Society; Tittl *et al.*, Science **360**, 1105–1109 (2018). Copyright 2018 American Association for the Advancement of Science.]

$$\frac{d}{dt}M = j\omega_m M - \gamma_m M + j\mu P, \tag{3}$$

$$s_t = s_{in} - \sqrt{\gamma_r}P, \quad s_r = \sqrt{\gamma_r}P, \tag{4}$$

$$T = \left|\frac{s_t}{s_{in}}\right|^2, \quad R = \left|\frac{s_r}{s_{in}}\right|^2, \tag{5}$$

where P and M are the amplitudes of plasmonic and vibrational modes, respectively. ω_0 and ω_m represent the resonance frequencies of plasmonic and vibrational modes, respectively. γ_r and γ_a denote the radiative and absorptive losses of nanoantennas, while γ_m is the absorptive loss of molecule. μ represents the coupling strength. T and R denote transmission and reflection spectra, which are related to the amplitude of incident light (s_{in}), transmitted light (s_t), and reflected light (s_r). From the above equations and several assumptions, Wei *et al.* developed a theoretical framework illustrating the importance of interplay of radiative and absorptive losses to achieve maximum molecular signals extracted from the far-field spectra.[76] Interestingly, they found that the optimal condition for largest molecule signals is dependent on whether transmission or reflection spectra are used. Guided by the valuable insights gained from the temporal coupled mode theory, we can divide the metamaterial sensors into three categories based on the material platforms: metals, semiconductors, and dielectrics.

Metals could have been the most widely used materials for designing metamaterial molecule sensors, due to their strong resonance strength, large field enhancement, and simple design principles.[30,77–82] These features are due to the high free electrons density in metals, which contribute a large negative part to the permittivity in the infrared range. Therefore, the design of metallic resonant nanostructures is quite similar to their counterparts in microwave or radiofrequency, and hence also called "nanoantennas."[83,84] Furthermore, multiple structures can be designed onto a single chip for simultaneous monitoring of various analytes, as shown in Fig. 3(a).[85] Importantly, the metals, e.g., gold, can be conveniently functionalized with bio-molecules, which are especially interesting for pharmacies and biochemical reactions. In 2019, Semenyshyn *et al.* demonstrated that the conformational changes of polypeptide can be captured in real time using infrared plasmonic nanoantennas.[86] More examples can also be found in other comprehensive reviews.[5] However, the metallic structures also possess several intrinsic drawbacks. First, the plasmon confinement at the surface of metals in infrared is poor, extending more than hundreds of nanometers, because of the large negative permittivity.[87] Second, the Ohmic loss in metals puts an upper limit on the quality factor of plasmonic resonators, usually below 20.[88–90]

Semiconductors, on the other hand, provide an approach to address the drawbacks of metals.[91,92] With a much lower charge density that can be electrically tunable, the plasmonic confinement in semiconductors is much better than metals, thereby leading to much higher near-field enhancement for sensing applications. As shown in Fig. 3(b), Rodrigo *et al.* reported tunable plasmonic biosensors based on graphene nanoribbons with extreme spatial light confinement that is two orders better than that of metals.[93] The unprecedentedly good overlap between local field and nanometric biomolecules allows superior sensitivity in the detection of both the refractive index and vibrational fingerprints. In addition to the sensing of bio-molecules, Hu *et al.* also demonstrated in 2019 that graphene plasmon shows superior performance in gas sensing.[94] Nevertheless, the low free charge density in semiconductors also bring a shortcoming that the resonance strength is relatively weak and less bright to the free space compared to metals. For example, the extinction ratio of graphene plasmons is usually below a few percent, one order weaker than metallic resonances.[95–97]

Recently, dielectric structures have been captivated as a promising platform to overcome the above issues.[98–100] Without Ohmic loss, dielectric resonators may show very high quality factors if properly designed.[101] Besides, the resonance in dielectric structures is based on the displacement of electric field, and the extinction may even approach unity. As shown in Fig. 3(c), Tittl *et al.* leveraged the ultra-high quality factor of silicon nanodisks that were judiciously designed on the concept of bound states in the continuum and demonstrated imaging-based detection of mid-infrared molecular fingerprints, and the device does not require spectrometry, frequency scanning, or moving mechanical parts.[33] In another work in 2018, Chang *et al.* reported an ultrasensitive CO_2 sensor based on an all-dielectric metamaterial integrated with an

enrichment polymer layer.[98] The detection limit reaches 20 ppm. However, since the resonance in dielectric structures is based on the electrical displacement, the majority of near field may not be exposed, which is detrimental for sensing applications. It has been studied that dielectric structures can be inferior than the metallic counterparts in sensing due to the poor field exposure.[102] Therefore, a strategic design would be critical for dielectric structures which is, however, not so straightforward as metallic structures due to the different mechanisms.

IV. FILTERS

In infrared spectroscopy, the optical signals encoded with molecular fingerprints should be demultiplexed in wavelength, which needs the spectral filter. Figure 4(a) shows the three generations of spectral filters. First, the gratings are still widely used especially in the visible range, but it requires a bulky volume for the diffracted light at different wavelengths to be well separated. Second, the Fourier transform infrared spectroscopy (FTIR) configuration shows advantages like relatively small footprint and broad working ranges. Miniaturization of FTIR is also one of the most intriguing research areas to implement compact devices including for sensing applications.[46,103,104] Recently, it is demonstrated that more compact devices may be designed with spectral filter arrays with different wavelength responsees.[31,105,106] Such research starts from 2015 when Bao *et al.* demonstrated this method for the first time using colloidal quantum dots in the visible range.[105] Following this pioneer work, Wang *et al.* demonstrated spectral filters based on photonic crystal slabs as shown in Fig. 4.[31] These photonic crystals are fabricated with silicon, which is compatible with complementary metal–oxide–semiconductor (CMOS) technology and hence can be mass produced at low costs. Beyond the visible range, such a concept can also be adapted in the infrared range.[107] For example, Shrestha *et al.* reported computational spectroscopy in the mid- to long-wave infrared based on a graphene metasurface modulator.[108] The spectral filters can be modulated by applying gate voltage and tuning the Fermi level of graphene. Although the modulation depth of graphene metasurface is not significant, a similar concept can be used in other material platforms for higher performance.

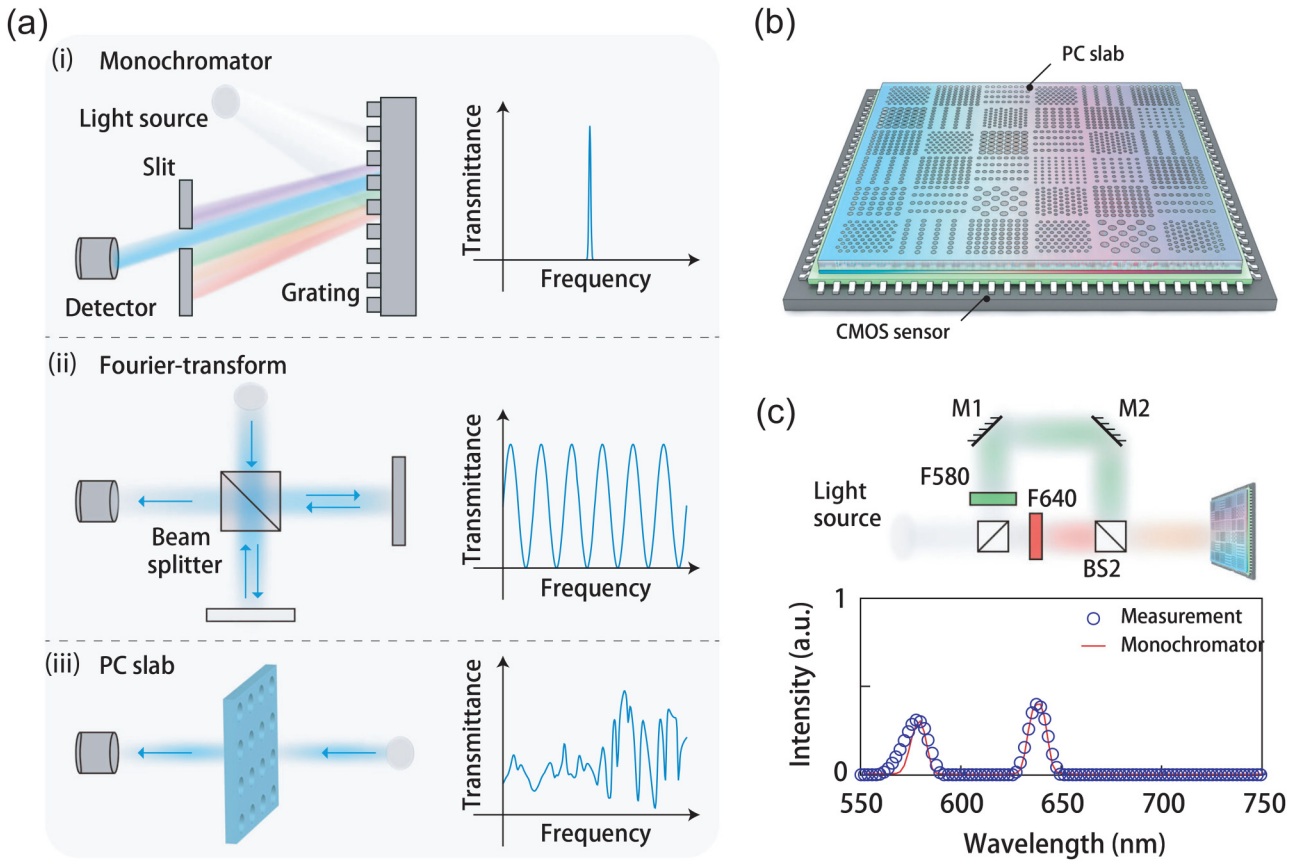

FIG. 4. Metamaterials for spectral filters. (a) Three generations of spectral filters. PC slab indicates photonic crystal slab. (b) Schematic of the metamaterial filters array. (c) Demonstration of spectrometer with metamaterial filters. BS means beam splitter. F580 and F640 represent calibrated bandpass filters with central wavelength at 580 nm and 640 nm, respectively. Reproduced with permission from Wang *et al.*, Nat. Commun. **10**, 1020 (2019). Copyright 2019 Springer Nature.

It is worth noting that although the spectral filter usually is a separate component in conventional infrared spectroscopy, more and more works have shown that it can also be intrinsically integrated with other components, such as light sources, sensors, and photodetectors.[33,109,110] In these scenarios, a set of components are required to cover the whole wavelength range of interest.

V. DETECTORS

In infrared spectroscopy, photodetectors translate the encoded optical signals into electrical signals for data analysis and output. Before we proceed to the recent works, we would like to first briefly introduce the figures of merit to characterize the performance of photodetectors, including responsivity, noise equivalent power (NEP), detectivity (D), and specific detectivity (D^*). The responsivity is defined as the ratio of output voltage or current and input optical power, in units of V/W or A/W, respectively. On the other hand, the performance of photodetectors is of course limited by their noise level. NEP is defined as the ratio of noise and responsivity, which gives the lowest power that a photodetector can detect. Conventionally, D is also defined as 1/NEP for a more convenient comparison. For many photodetectors, their noise may be proportional to their device area so that the performances of small devices are overestimated. To fairly compare such devices with different areas, D^* should be used, which is the product of square root of device area and detectivity, $D^* = A^{1/2}D$.[111] Metamaterials play two key roles in the photodetectors especially for miniaturized infrared spectroscopy, that is, the enhancement of performance and the enrichment of functionalities, as shown in Fig. 5.

Metamaterial has manifested itself as a powerful tool to enhance the performance of photodetectors for a variety of mechanism, including photovoltaic effect, photo-thermoelectric effect, photoconductive effect, and bolometric effect.[112–116] The enhancement allows photodetectors to work efficiently even with a smaller device area.[117–121] In addition to the enhancement in absorption, engineered nanostructures can also bring many intriguing phenomena, e.g., hot electrons.[122] As shown in Fig. 5(a), Knight *et al.* reported a very compact method to generate photocurrent by combining two distinct components, i.e., optical nanoantennas and diodes.[123] In their design, "hot" electrons are generated from nonradiative decay of plasmons and then injected over a potential barrier. Besides, metamaterials have also been used to enhance the performance of the photo-thermoelectric effect, which is preferred in many occasions due to the bandgap-unlimited photodetection mechanism.[124–126] As in Fig. 5(b), Mauser *et al.* reported that structured bismuth telluride/antimony telluride and chromel/alumel can show high responsivity of 38 V/W and wavelength-specific dependence.[124] Two more examples of performance enhancement via metamaterials are shown in Figs. 5(c) and 5(d), namely, photoconducting and bolometric effects, respectively. In Fig. 5(c), the excitation and decay of plasmons in nano-structured graphene lead to a significant change in the conductance.[127] Strikingly, the reported device has a small subwavelength footprint of only $5 \times 5\,\mu m^2$ and a low NEP of $1.3\,nW\,Hz^{-1/2}$ at $12.2\,\mu m$ wavelength. In Fig. 5(d), Efetov *et al.* demonstrated that the bolometric response in ultraclean graphene can be significantly enhanced by critically coupling to a photonic nanocavity with a quality factor of 900.[128] At 5 K, the noise equivalent power reaches about $10\,pW\,Hz^{-1/2}$ and a record fast thermal relaxation time, <35 ps. In summary, the subwavelength structures enable efficient light absorption even with a small footprint, making it possible to miniaturize the device size substantially.

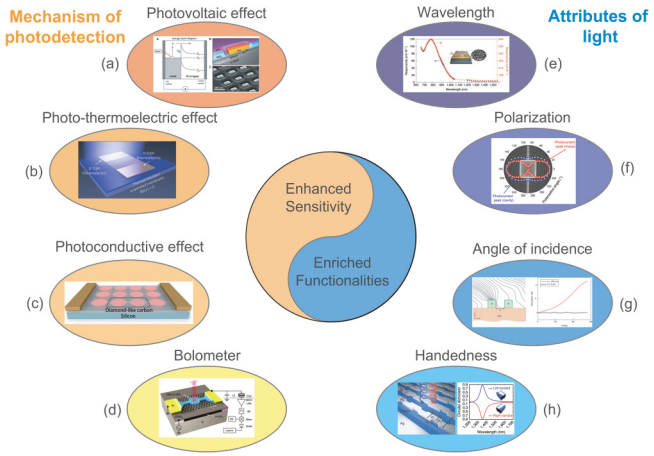

FIG. 5. Metamaterials for photodetectors. Metamaterial-mediated photodetectors possess two main unique advantages, namely, enhanced sensitivity and enriched functionalities. On the one hand, the enhancement has been manifested in detectors with various mechanisms: (a) photovoltaic effect, (b) photo-thermoelectric effect, (c) photoconductive effect, (d) bolometer. On the other hand, the design flexibility of metamaterials endows the detectors with rich functionalities, allowing us to detect other attributes of light beyond intensity, such as (e) wavelength, (f) polarization, (g) angle of incidence, and (h) handedness. [(a) Reproduced with permission from Knight *et al.*, Science **332**, 702–704 (2011). Copyright 2011 American Association for the Advancement of Science; (b) Reproduced with permission from Mauser *et al.*, Nat. Nanotechnol. **12**, 770–775 (2017). Copyright 2017 Springer Nature; (c) Reproduced with permission from Guo *et al.*, Nat. Mater. **17**, 986–992 (2018). Copyright 2018 Springer Nature; (d) Reproduced with permission from Efetov *et al.*, Nat. Nanotechnol. **13**, 797–801 (2018). Copyright 2018 Springer Nature; (e) Reproduced with permission from Stewart *et al.*, Nat. Mater. **19**, 158–162 (2020). Copyright 2020 Springer Nature; (f) Reproduced with permission from Palaferri *et al.*, Nature **556**, 85–88 (2018). Copyright 2018 Springer Nature; (g) Reproduced with permission from Yi *et al.*, Nat. Nanotechnol. **13**, 1143–1147 (2018). Copyright 2018 Springer Nature; (h) Reproduced with permission from Li *et al.*, Nat. Commun. **6**, 8379 (2015). Copyright 2015 Springer Nature.

In addition to the light intensity, it is also highly desired in many cases that the photodetectors can detect the other attributes of light, including wavelength, polarization, handedness, the angle of incidence, and even orbit angular momentum.[28,129–132] Conventionally, the detection of such attributes needs additional optical components, e.g., wave plates and polarizers, and hence makes the whole setup bulky. In the past few years, we have seen increasing efforts in designing functional photodetectors using metamaterials that are wavelength-specific, polarization-sensitive, and so on.[125,133,134] For example, Stewart *et al.* reported a pyroelectric photodetector with intrinsic spectral filters that cover the visible and near-infrared ranges, as Fig. 5(e).[110] In Fig. 5(f), Palaferri *et al.* demonstrated metamaterial-enhanced quantum well photodetectors in the mid-infrared range which features an

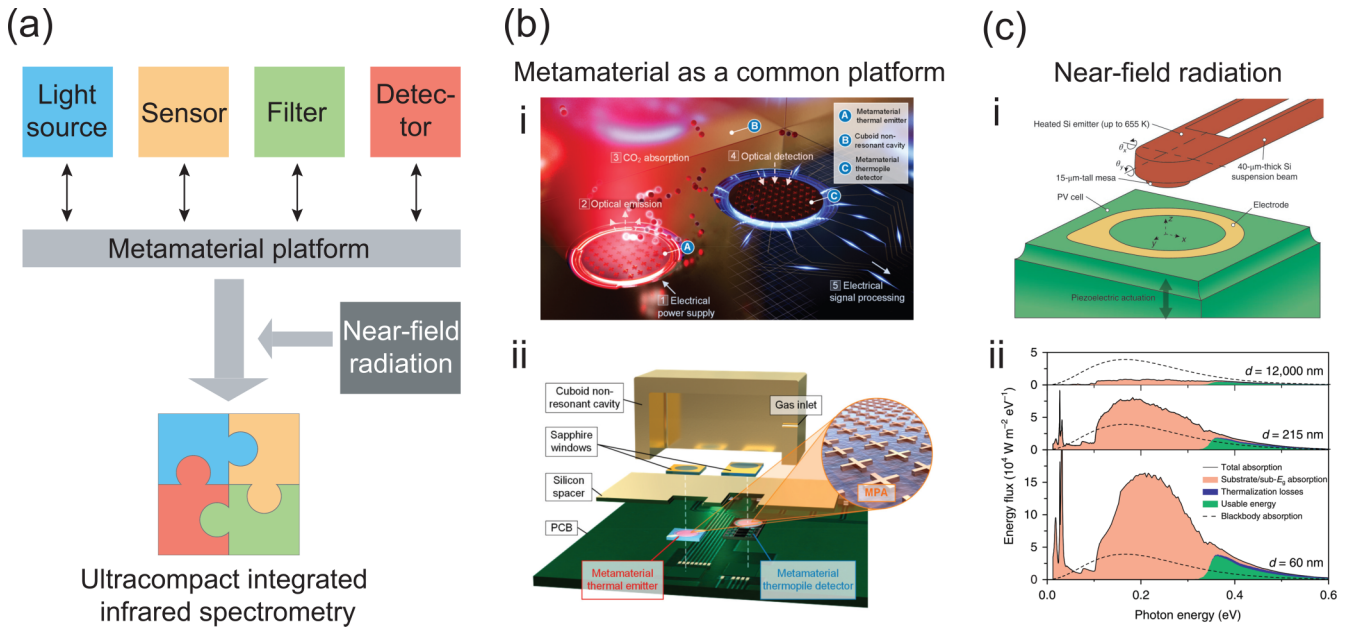

FIG. 6. Metamaterials for integrated devices. (a) Possible opportunities for ultracompact integrated spectrometry via metamaterials. Most importantly, the metamaterials may act as a common platform to bridge the different components. Besides, the near-field radiation should be considered when the dimension of device is smaller than the wavelength of radiation. (b) Recent advances that leverage the common platform of metamaterials to shrink the size of infrared spectrometry. Reproduced with permission from Lochbaum *et al.*, Nano Lett. **20**(6), 4169–4176 (2020). Copyright 2020 American Chemical Society. (c) Recent studies on near-field radiation that can surpasses the limit of Planck's radiation law. The near-field radiation will also bring increased matter–light interaction and can be harvested by near-field photodetectors. Reproduced with permission from Fiorino *et al.*, Nat. Nanotechnol. **13**, 806–811 (2018). Copyright 2018, Springer Nature.

adjustable polarization dependence.[116] In Fig. 5(g), Yi *et al.* showed that a planar photodetector can even detect the incidence of angle via non-Hermitian coupling, mimicking the hearing of small animals.[135] In Fig. 5(h), Li *et al.* reported a chiral plasmonic metamaterial photodetector that can resolve the handedness of incident light without using waveplates or polarizers.[136] Such rich functionalities enabled by metamaterials may allow miniaturized infrared spectroscope to remove the filter parts and hence become more compact.

VI. INTEGRATION

In traditional infrared spectroscopy, the light sources, sensors, filters, and detectors are fabricated based on distinct processes and materials, making the whole system complicated and bulky.[1,14] As we have reviewed in this Perspective, metamaterials have played key roles in all the components, relaxing the restrictions in materials selection. For example, CMOS compatibility has been demonstrated in all metamaterial-based light sources,[32,51] sensors,[33,137] filters,[31] and detectors.[29,34] Therefore, these components are able to be fabricated through similar processes so that the overall cost ought to be decreased. In this scenario, metamaterials act as a general platform as shown in Fig. 6(a). In fact, we have seen several pioneering works in this direction. As shown in Fig. 6(b), Lochbaum *et al.* showed that the thermal emitters and thermopile detectors can be fabricated and integrated on a single chip, demonstrating a sensitive CO_2 monitor with a sensitivity of $22.4 \pm 0.5\ \text{ppm}\cdot\text{Hz}^{-0.5}$.[138] Compared to conventional methods, the absorption volume is reduced by 30 times. In future, plasmonic sensors may be further integrated into the system to realize a more compact device.[76,98]

An interesting question is what may occur when the individual components approach each other in such a distance that is comparable to the wavelength of light. In this case, the usually ignored non-radiative optical field becomes to be dominant, and the energy transfer between neighboring components can be boosted. For example, super-Planckian radiation between objects with nanoscale gaps have been a very hot research area now.[139–141] As shown in Fig. 6(c), Fiorino *et al.* demonstrated that the overall power harvested by a thermopile detector was increased by 40 times when the distance between thermal emitter and detector is about 60 nm.[142] In other words, the field intensity can be enhanced by several orders in miniaturized devices, which is highly useful for infrared spectroscopy.

VII. OUTLOOK AND DISCUSSION

Looking forward, we believe that the true potential of miniaturized infrared spectroscopy could be realized in metamaterial-based devices with sub-wavelength sizes. As the first step, an interesting question arises to whether the near-field boosted thermal transfer can be used for sensing applications. While thermal radiation usually requires heated sources with very high temperatures, it

faces challenges in being packaged with other components in a very small footprint. Therefore, thermal emission based on hot electrons is more favorable where the lattice stays cool. Alternatively, cool lights such as photoluminescence and lasing may also be enhanced by near field radiation, but their applications for sensing remain elusive. To date, the sub-wavelength integration of light sources and detectors has not been demonstrated, not to mention the use of such a compact configuration for sensing applications. In addition, although we are excited to see emerging novel designs of ultrahigh-Q dielectric resonators based on BIC, most existing works were focused on the engineering of far-field radiation, while the BIC in the near field region is not well studied. When more objects are placed at the vicinity of the BIC cavity, the BIC could be broken, leading to much lower Q values. Furthermore, the development of thin-film deposition of porous organic frameworks including metal-organic framework (MOF) and covalent-organic framework (COF) on such dielectric resonators would be interesting, especially for gas sensing which needs enrichment layer. Besides, it is also interesting to use machine learning or neural network to help differentiate the contribution of multiple analytes. Due to the large near field intensity, the absorption of analytes may become nonlinear so that conventional principal components analysis becomes invalid. Finally, although the monolithic integration of all four components remains challenging, we may start from the integration of two or three components. For example, it should be technically easy to use plasmon-enhanced photodetectors for liquid or gas sensing applications, since the plasmon will also enhance the absorption of analytes in a similar way. With the light source coming through free space propagation, the sensing device itself could be ultracompact, which may be useful for specific cases such as remote sensing.

VIII. CONCLUSION

By reviewing the recent advances in metamaterial-based infrared spectroscopy, we point it out that metamaterials, or engineered nanostructures, offer exciting possibilities for miniaturized infrared spectroscopy with unprecedented compactness. Specifically, we raise two main advantages of this approach. First, since metamaterials are basically artificially engineered structures, the restrictions in the material selection are relaxed so that different components now can share similar fabrication processes at a lower cost. Second, the designed resonators usually feature strong local field which is perfect to be leveraged with the nascent near-field radiation, and hence the sensitivity of infrared spectroscopy can be maintained or even increased when the whole absorption volume decreases. We hope that this Perspective can provide valuable insights into this field and fuel the research in this direction.

ACKNOWLEDGMENTS

This work was supported by NRF-CRP15-2015-02 "Piezoelectric Photonics Using CMOS Compatible AlN Technology for Enabling the Next Generation Photonics ICs and Nanosensors" (WBS: R-263000C24281) at the National University of Singapore, Singapore; and the A*STAR-NCBR research grant of "Chip-Scale MEMS Micro-Spectrometer for Monitoring Harsh Industrial Gases" (Grant No. A18A5b0056; WBS R-263-000-D78-305) at the NUS, Singapore.

DATA AVAILABILITY

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

REFERENCES

[1]B. Stuart, in *Kirk-Othmer Encyclopedia of Chemical Technology* (John Wiley & Sons, Inc., Hoboken, NJ, 2015), pp. 1–18.
[2]I. Pupeza, M. Huber, M. Trubetskov, W. Schweinberger, S. A. Hussain, C. Hofer, K. Fritsch, M. Poetzlberger, L. Vamos, E. Fill, T. Amotchkina, K. V. Kepesidis, A. Apolonski, N. Karpowicz, V. Pervak, O. Pronin, F. Fleischmann, A. Azzeer, M. Žigman, and F. Krausz, Nature **577**, 52 (2020).
[3]S. H. Oh and H. Altug, Nat. Commun. **9**, 1 (2018).
[4]J. L. Lansford and D. G. Vlachos, Nat. Commun. **11**, 5263 (2020).
[5]F. Neubrech, C. Huck, K. Weber, A. Pucci, and H. Giessen, Chem. Rev. **117**, 5110 (2017).
[6]X. Liu, W. Wang, Y. Zhang, Y. Pan, Y. Liang, and J. Li, Sensors **18**, 3796 (2018).
[7]F. Schedin, A. K. Geim, S. V. Morozov, E. W. Hill, P. Blake, M. I. Katsnelson, and K. S. Novoselov, Nat. Mater. **6**, 652 (2007).
[8]C. Viespe and D. Miu, Sensors **17**, 1529 (2017).
[9]S. Okuda, T. Ono, Y. Kanai, T. Ikuta, M. Shimatani, S. Ogawa, K. Maehashi, K. Inoue, and K. Matsumoto, ACS Sensors **3**, 200 (2018).
[10]C. Wang, C. Wang, D. Jin, Y. Yu, F. Yang, Y. Zhang, Q. Yao, and G.-J. Zhang, ACS Sensors **5**, 362 (2020).
[11]T.-V. Dinh, I.-Y. Choi, Y.-S. Son, and J.-C. Kim, Sensors Actuators B Chem. **231**, 529 (2016).
[12]M. Rauscher, A. Tremmel, M. Schardt, and A. Koch, Sensors **17**, 399 (2017).
[13]R. Adato, H. Altug, H. Altug, G. S. Kino, W. E. Moerner, and J. Aizpurua, Nat. Commun. **4**, 2154 (2013).
[14]S.-S. Kim, C. Young, and B. Mizaikoff, Anal. Bioanal. Chem. **390**, 231 (2008).
[15]C. Chen, X. Lu, B. Deng, X. Chen, Q. Guo, C. Li, C. Ma, S. Yuan, E. Sung, K. Watanabe, T. Taniguchi, L. Yang, and F. Xia, Sci. Adv. **6**, eaay6134 (2020).
[16]J. Wei, F. Sun, B. Dong, Y. Ma, Y. Chang, H. Tian, and C. Lee, Opt. Lett. **43**, 5407 (2018).
[17]M. Sieger and B. Mizaikoff, Anal. Chem. **88**, 5562 (2016).
[18]T. Hu, B. Dong, X. Luo, T.-Y. Liow, J. Song, C. Lee, and G.-Q. Lo, Photonics Res. **5**, 417 (2017).
[19]B. Dong, X. Luo, S. Zhu, M. Li, D. Hasan, L. Zhang, S. J. Chua, J. Wei, Y. Chang, G.-Q. Lo, K. W. Ang, D.-L. Kwong, and C. Lee, Opt. Lett. **44**, 73 (2019).
[20]H. Lin, Z. Luo, T. Gu, L. C. Kimerling, K. Wada, A. Agarwal, and J. Hu, Nanophotonics **7**, 393 (2017).
[21]Y. Chang, J. Wei, and C. Lee, Nanophotonics **9**, 3049 (2020).
[22]Z. Ren, Y. Chang, Y. Ma, K. Shih, B. Dong, and C. Lee, Adv. Opt. Mater. **8**, 1900653 (2020).
[23]G. Dayal, X. Y. Chin, C. Soci, and R. Singh, Adv. Opt. Mater. **5**, 1600559 (2017).
[24]F. Liang and Q. Quan, ACS Photonics **2**, 1692 (2015).
[25]P. B. Deotare, M. W. McCutcheon, I. W. Frank, M. Khan, and M. Lončar, Appl. Phys. Lett. **94**, 121106 (2009).
[26]J. Heebner, R. Grover, T. Ibrahim, and T. A. Ibrahim, *Optical Microresonators: Theory, Fabrication, and Applications* (Springer Science & Business Media, 2008).
[27]A. F. Koenderink, A. Alù, and A. Polman, Science **348**, 516 (2015).
[28]Y. Zhao, A. N. Askarpour, L. Sun, J. Shi, X. Li, and A. Alù, Nat. Commun. **8**, 14180 (2017).
[29]P. S. Davids, J. Kirsch, A. Starbuck, R. Jarecki, J. Shank, and D. Peters, Science **367**, 1341 (2020).
[30]D. Hasan, P. Pitchappa, C. Pei Ho, and C. Lee, Adv. Opt. Mater. **5**, 1600778 (2017).
[31]Z. Wang, S. Yi, A. Chen, M. Zhou, T. S. Luk, A. James, J. Nogan, W. Ross, G. Joe, A. Shahsafi, K. X. Wang, M. A. Kats, and Z. Yu, Nat. Commun. **10**, 1020 (2019).

[32]S. Wu, S. Buckley, J. R. Schaibley, L. Feng, J. Yan, D. G. Mandrus, F. Hatami, W. Yao, J. Vučković, A. Majumdar, and X. Xu, Nature **520**, 69 (2015).
[33]A. Tittl, A. Leitis, M. Liu, F. Yesilkoy, D.-Y. Choi, D. N. Neshev, Y. S. Kivshar, and H. Altug, Science **360**, 1105 (2018).
[34]S. Goossens, G. Navickaite, C. Monasterio, S. Gupta, J. J. Piqueras, R. Pérez, G. Burwell, I. Nikitskiy, T. Lasanta, T. Galán, E. Puma, A. Centeno, A. Pesquera, A. Zurutuza, G. Konstantatos, and F. Koppens, Nat. Photonics **11**, 366 (2017).
[35]D. Wang, W. Wang, M. P. Knudson, G. C. Schatz, and T. W. Odom, Chem. Rev. **118**, 2865 (2018).
[36]G. Crosnier, D. Sanchez, S. Bouchoule, P. Monnier, G. Beaudoin, I. Sagnes, R. Raj, and F. Raineri, Nat. Photonics **11**, 297 (2017).
[37]B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics* (John Wiley & Sons, Inc., New York, 1991).
[38]O. Painter, R. K. Lee, A. Scherer, A. Yariv, J. D. O'Brien, R. D. Dapkus, and I. Kim, Science **284**, 1819 (1999).
[39]M. Khajavikhan, A. Simic, M. Katz, J. H. Lee, B. Slutsky, A. Mizrahi, V. Lomakin, and Y. Fainman, Nature **482**, 204 (2012).
[40]B. Ellis, M. A. Mayer, G. Shambat, T. Sarmiento, J. Harris, E. E. Haller, and J. Vučković, Nat. Photonics **5**, 297 (2011).
[41]H.-G. Park, S.-H. Kim, S.-H. Kwon, Y.-G. Ju, J.-K. Yang, J.-H. Baek, S.-B. Kim, and Y.-H. Lee, Science **305**, 1444 (2004).
[42]R.-M. Ma and R.-F. Oulton, Nat. Nanotechnol. **14**, 12 (2019).
[43]A. Kodigala, T. Lepetit, Q. Gu, B. Bahari, Y. Fainman, and B. Kanté, Nature **541**, 196 (2017).
[44]S. T. Ha, Y. H. Fu, N. K. Emani, Z. Pan, R. M. Bakker, R. Paniagua-Domínguez, and A. I. Kuznetsov, Nat. Nanotechnol. **13**, 1042 (2018).
[45]M. A. Fusella, R. Saramak, R. Bushati, V. M. Menon, M. S. Weaver, N. J. Thompson, and J. J. Brown, Nature **585**, 379 (2020).
[46]D. M. Kita, B. Miranda, D. Favela, D. Bono, J. Michon, H. Lin, T. Gu, and J. Hu, Nat. Commun. **9**, 1 (2018).
[47]D. M. Kita, H. Lin, A. Agarwal, K. Richardson, I. Luzinov, T. Gu, and J. Hu, IEEE J. Sel. Top. Quantum Electron. **23**, 340 (2017).
[48]C. Chen, D. A. Mohr, H.-K. Choi, D. Yoo, M. Li, and S.-H. Oh, Nano Lett. **18**, 7601 (2018).
[49]M. Yu, Y. Okawachi, A. G. Griffith, N. Picqué, M. Lipson, and A. L. Gaeta, Nat. Commun. **9**, 6 (2018).
[50]Y. Yu, W. Xue, E. Semenova, K. Yvind, and J. Mork, Nat. Photonics **11**, 81 (2017).
[51]A. Lochbaum, Y. Fedoryshyn, A. Dorodnyy, U. Koch, C. Hafner, and J. Leuthold, ACS Photonics **4**, 1371 (2017).
[52]T. Mori, Y. Yamauchi, S. Honda, and H. Maki, Nano Lett. **14**, 3277 (2014).
[53]E. Sakat, L. Wojszvzyk, J.-P. Hugonin, M. Besbes, C. Sauvan, and J.-J. Greffet, Optica **5**, 175 (2018).
[54]M. Freitag, H.-Y. Chiu, M. Steiner, V. Perebeinos, and P. Avouris, Nat. Nanotechnol. **5**, 497 (2010).
[55]D. G. Baranov, Y. Xiao, I. A. Nechepurenko, A. Krasnok, A. Alù, and M. A. Kats, Nat. Mater. **18**, 920 (2019).
[56]X. Liu, T. Tyler, T. Starr, A. F. Starr, N. M. Jokerst, and W. J. Padilla, Phys. Rev. Lett. **107**, 045901 (2011).
[57]T. Inoue, M. De Zoysa, T. Asano, and S. Noda, Nat. Mater. **13**, 928 (2014).
[58]X. Liu and W. J. Padilla, Adv. Opt. Mater. **1**, 559 (2013).
[59]J.-J. Greffet, R. Carminati, K. Joulain, J.-P. Mulet, S. Mainguy, and Y. Chen, Nature **416**, 61 (2002).
[60]J. Li, B. Yu, and S. Shen, Phys. Rev. Lett. **124**, 137401 (2020).
[61]V. W. Brar, M. C. Sherrott, M. S. Jang, S. Kim, L. Kim, M. Choi, L. A. Sweatlock, and H. A. Atwater, Nat. Commun. **6**, 7032 (2015).
[62]O. Ilic, P. Bermel, G. Chen, J. D. Joannopoulos, I. Celanovic, and M. Soljačić, Nat. Nanotechnol. **11**, 320 (2016).
[63]X. Liu and W. J. Padilla, Optica **4**, 430 (2017).
[64]Y. Qu, Q. Li, K. Du, L. Cai, J. Lu, and M. Qiu, Laser Photon. Rev. **11**, 1700091 (2017).
[65]Y. Xiao, N. A. Charipar, J. Salman, A. Piqué, and M. A. Kats, Light Sci. Appl. **8**, 1 (2019).
[66]R.-J. Shiue, Y. Gao, C. Tan, C. Peng, J. Zheng, D. K. Efetov, Y. D. Kim, J. Hone, and D. Englund, Nat. Commun. **10**, 109 (2019).
[67]L. S. Fohrmann, A. Y. Petrov, S. Lang, D. Jalas, T. F. Krauss, and M. Eich, Opt. Express **23**, 27672 (2015).
[68]F. Pyatkov, V. Fütterling, S. Khasminskaya, B. S. Flavel, F. Hennrich, M. M. Kappes, R. Krupke, and W. H. P. Pernice, Nat. Photonics **10**, 420 (2016).
[69]F. Neubrech, A. Pucci, T. W. Cornelius, S. Karim, A. García-Etxarri, and J. Aizpurua, Phys. Rev. Lett. **101**, 2 (2008).
[70]D. Yoo, D. A. Mohr, F. Vidal-Codina, A. John-Herpin, M. Jo, S. Kim, J. Matson, J. D. Caldwell, H. Jeon, N.-C. Nguyen, L. Martin-Moreno, J. Peraire, H. Altug, and S.-H. Oh, Nano Lett. **18**, 1930 (2018).
[71]L. Dong, X. Yang, C. Zhang, B. Cerjan, L. Zhou, M. L. Tseng, Y. Zhang, A. Alabastri, P. Nordlander, and N. J. Halas, Nano Lett. **17**(9), 5768–5774 (2017).
[72]L. V. Brown, X. Yang, K. Zhao, B. Y. Zheng, P. Nordlander, and N. J. Halas, Nano Lett. **15**, 1272 (2015).
[73]H. A. Haus, *Waves and Fields in Optoelectronics* (Prentice-Hall, 1984).
[74]S. Fan, W. Suh, and J. D. Joannopoulos, J. Opt. Soc. Am. A **20**, 569 (2003).
[75]R. Adato, A. Artar, S. Erramilli, and H. Altug, Nano Lett. **13**, 2584 (2013).
[76]J. Wei, Y. Li, Y. Chang, D. M. N. Hasan, B. Dong, Y. Ma, C. W. Qiu, and C. Lee, ACS Appl. Mater. Interfaces **11**, 47270 (2019).
[77]D. Hasan and C. Lee, Adv. Sci. **5**, 1700581 (2018).
[78]C. Wu, A. B. Khanikaev, R. Adato, N. Arju, A. A. Yanik, H. Altug, and G. Shvets, Nat. Mater. **11**, 69 (2012).
[79]C. Huck, J. Vogt, M. Sendner, D. Hengstler, F. Neubrech, and A. Pucci, ACS Photonics **2**, 1489 (2015).
[80]L. V. Brown, K. Zhao, N. King, H. Sobhani, P. Nordlander, and N. J. Halas, J. Am. Chem. Soc. **135**, 3688 (2013).
[81]K. Chen, R. Adato, and H. Altug, ACS Nano **6**, 7998 (2012).
[82]R. Adato, A. A. Yanik, J. J. Amsden, D. L. Kaplan, F. G. Omenetto, M. K. Hong, S. Erramilli, and H. Altug, Proc. Natl. Acad. Sci. U.S.A. **106**, 19227 (2009).
[83]P. Mühlschlegel, H.-J. Eisler, O. J. F. Martin, B. Hecht, and D. W. Pohl, Science **308**, 1607 (2005).
[84]L. Novotny, Phys. Rev. Lett. **98**, 266802 (2007).
[85]D. Rodrigo, A. Tittl, N. Ait-Bouziad, A. John-Herpin, O. Limaj, C. Kelly, D. Yoo, N. J. Wittenberg, S.-H. Oh, H. A. Lashuel, and H. Altug, Nat. Commun. **9**, 2160 (2018).
[86]R. Semenyshyn, M. Hentschel, C. Stanglmair, T. Teutsch, C. Tarin, C. Pacholski, H. Giessen, and F. Neubrech, Nano Lett. **19**, 1 (2019).
[87]R. Stanley, Nat. Photonics **6**, 409 (2012).
[88]D. Hasan, P. Pitchappa, J. Wang, T. Wang, B. Yang, C. P. Ho, and C. Lee, ACS Photonics **4**, 302 (2017).
[89]S. Kang, Z. Qian, V. Rajaram, S. D. Calisgan, A. Alù, and M. Rinaldi, Adv. Opt. Mater. **7**, 1801236 (2019).
[90]J. Xu, Z. Ren, B. Dong, X. Liu, C. Wang, Y. Tian, and C. Lee, ACS Nano **14**, 12159 (2020).
[91]H. Hu, X. Yang, F. Zhai, D. Hu, R. Liu, K. Liu, Z. Sun, and Q. Dai, Nat. Commun. **7**, 12334 (2016).
[92]X. Yang, Z. Sun, T. Low, H. Hu, X. Guo, F. J. García de Abajo, P. Avouris, and Q. Dai, Adv. Mater. **30**, 1704896 (2018).
[93]D. Rodrigo, O. Limaj, D. Janner, D. Etezadi, F. J. García de Abajo, V. Pruneri, and H. Altug, Science **349**, 165 (2015).
[94]H. Hu, X. Yang, X. Guo, K. Khaliji, S. R. Biswas, F. J. García de Abajo, T. Low, Z. Sun, and Q. Dai, Nat. Commun. **10**, 1131 (2019).
[95]T. Low and P. Avouris, ACS Nano **8**, 1086 (2014).
[96]H. Yan, T. Low, W. Zhu, Y. Wu, M. Freitag, X. Li, F. Guinea, P. Avouris, and F. Xia, Nat. Photonics **7**, 394 (2013).
[97]J. Schiefele, J. Pedrós, F. Sols, F. Calle, and F. Guinea, Phys. Rev. Lett. **111**, 237405 (2013).
[98]Y. Chang, D. Hasan, B. Dong, J. Wei, Y. Ma, G. Zhou, K. W. Ang, and C. Lee, ACS Appl. Mater. Interfaces **10**, 38272 (2018).

[99]S. Romano, G. Zito, S. Torino, G. Calafiore, E. Penzo, G. Coppola, S. Cabrini, I. Rendina, and V. Mocella, Photonics Res. **6**, 726 (2018).
[100]J. Hu, T. Lang, and G.-H. Shi, Opt. Express **25**, 15241 (2017).
[101]K. Koshelev, S. Lepeshov, M. Liu, A. Bogdanov, and Y. Kivshar, Phys. Rev. Lett. **121**, 193903 (2018).
[102]N. Bosio, H. Šípová-Jungová, N. O. Länk, T. J. Antosiewicz, R. Verre, and M. Käll, ACS Photonics **6**, 1556 (2019).
[103]A. Fathy, Y. M. Sabry, S. Nazeer, T. Bourouina, and D. A. Khalil, Microsys. Nanoeng. **6**, 1 (2020).
[104]E. Heidari, X. Xu, C.-J. Chung, and R. T. Chen, Opt. Lett. **44**, 2883 (2019).
[105]J. Bao and M. G. Bawendi, Nature **523**, 67 (2015).
[106]X. Chong, E. Li, K. Squire, and A. X. Wang, Appl. Phys. Lett. **108**, 221106 (2016).
[107]J. J. Cadusch, J. Meng, B. J. Craig, V. R. Shrestha, and K. B. Crozier, Nanophotonics **9**, 3197 (2020).
[108]V. R. Shrestha, B. Craig, J. Meng, J. Bullock, A. Javey, and K. B. Crozier, Sci. Rep. **10**, 5377 (2020).
[109]Z. Yang, T. Albrow-Owen, H. Cui, J. Alexander-Webber, F. Gu, X. Wang, T. Wu, M. Zhuge, C. Williams, P. Wang, A. V. Zayats, W. Cai, L. Dai, S. Hofmann, M. Overend, L. Tong, Q. Yang, Z. Sun, and T. Hasan, Science **365**, 1017 (2019).
[110]J. W. Stewart, J. H. Vella, W. Li, S. Fan, and M. H. Mikkelsen, Nat. Mater. **19**, 158 (2020).
[111]R. Jones, Proc. IRE **47**, 1495 (1959).
[112]T. J. Echtermeyer, L. Britnell, P. K. Jasnos, A. Lombardo, R. V. Gorbachev, A. N. Grigorenko, A. K. Geim, A. C. Ferrari, and K. S. Novoselov, Nat. Commun. **2**, 455 (2011).
[113]P. K. Venuthurumilli, P. D. Ye, and X. Xu, ACS Nano **12**, 4861 (2018).
[114]Y. Yao, R. Shankar, P. Rauter, Y. Song, J. Kong, M. Loncar, and F. Capasso, Nano Lett. **14**, 3749 (2014).
[115]S. Cakmakyapan, P. K. Lu, A. Navabi, and M. Jarrahi, Light Sci. Appl. **7**, 20 (2018).
[116]D. Palaferri, Y. Todorov, A. Bigioli, A. Mottaghizadeh, D. Gacemi, A. Calabrese, A. Vasanelli, L. Li, A. G. Davies, E. H. Linfield, F. Kapsalidis, M. Beck, J. Faist, and C. Sirtori, Nature **556**, 85 (2018).
[117]D. R. Ward, F. Hüser, F. Pauly, J. C. Cuevas, and D. Natelson, Nat. Nanotechnol. **5**, 732 (2010).
[118]P. S. Davids, R. L. Jarecki, A. Starbuck, D. Bruce Burckel, E. A. Kadlec, T. Ribaudo, E. A. Shaner, and D. W. Peters, Nat. Nanotechnol. **10**, 1033 (2015).
[119]A. Sharma, V. Singh, T. L. Bougher, and B. A. Cola, Nat. Nanotechnol. **10**, 1027 (2015).
[120]Y. Zhu, Z. Li, Z. Hao, C. DiMarco, P. Maturavongsadit, Y. Hao, M. Lu, A. Stein, Q. Wang, J. Hone, N. Yu, and Q. Lin, Light Sci. Appl. **7**, 67 (2018).
[121]P. Ma, Y. Salamin, B. Baeuerle, A. Josten, W. Heni, A. Emboras, and J. Leuthold, ACS Photonics **6**, 154 (2019).
[122]M. L. Brongersma, N. J. Halas, and P. Nordlander, Nat. Nanotechnol. **10**, 25 (2015).
[123]M. W. Knight, H. Sobhani, P. Nordlander, and N. J. Halas, Science **332**, 702 (2011).
[124]K. W. Mauser, S. Kim, S. Mitrovic, D. Fleischman, R. Pala, K. C. Schwab, and H. A. Atwater, Nat. Nanotechnol. **12**, 770 (2017).
[125]F. Lu, J. Lee, A. Jiang, S. Jung, and M. A. Belkin, Nat. Commun. **7**, 12994 (2016).
[126]V. Shautsova, T. Sidiropoulos, X. Xiao, N. A. Güsken, N. C. G. Black, A. M. Gilbertson, V. Giannini, S. A. Maier, L. F. Cohen, and R. F. Oulton, Nat. Commun. **9**, 5190 (2018).
[127]Q. Guo, R. Yu, C. Li, S. Yuan, B. Deng, F. J. García de Abajo, and F. Xia, Nat. Mater. **17**, 986 (2018).
[128]D. K. Efetov, R.-J. Shiue, Y. Gao, B. Skinner, E. D. Walsh, H. Choi, J. Zheng, C. Tan, G. Grosso, C. Peng, J. Hone, K. C. Fong, and D. Englund, Nat. Nanotechnol. **13**, 797 (2018).
[129]E. Hendry, T. Carpy, J. Johnston, M. Popland, R. V. Mikhaylovskiy, A. J. Lapthorn, S. M. Kelly, L. D. Barron, N. Gadegaard, and M. Kadodwala, Nat. Nanotechnol. **5**, 783 (2010).
[130]Z. Ji, W. Liu, S. Krylyuk, X. Fan, Z. Zhang, A. Pan, L. Feng, A. Davydov, and R. Agarwal, Science **368**, 763 (2020).
[131]J. Bullock, M. Amani, J. Cho, Y.-Z. Chen, G. H. Ahn, V. Adinolfi, V. R. Shrestha, Y. Gao, K. B. Crozier, Y.-L. Chueh, and A. Javey, Nat. Photonics **12**, 601 (2018).
[132]N. A. Rubin, G. D'Aversa, P. Chevalier, Z. Shi, W. T. Chen, and F. Capasso, Science **365**, eaax1839 (2019).
[133]F. Afshinmanesh, J. S. White, W. Cai, and M. L. Brongersma, Nanophotonics **1**, 125 (2012).
[134]E. Panchenko, J. J. Cadusch, T. D. James, and A. Roberts, ACS Photonics **3**, 1833 (2016).
[135]S. Yi, M. Zhou, Z. Yu, P. Fan, N. Behdad, D. Lin, K. X. Wang, S. Fan, and M. Brongersma, Nat. Nanotechnol. **13**, 1143 (2018).
[136]W. Li, Z. J. Coppens, L. V. Besteiro, W. Wang, A. O. Govorov, and J. Valentine, Nat. Commun. **6**, 8379 (2015).
[137]A. Samarelli, M. Ortolani, L. Baldassarre, J. Frigerio, G. Isella, E. Calandrini, D. J. Paul, K. Gallacher, E. Sakat, and P. Biagioni, Nano Lett. **15**, 7225 (2015).
[138]A. Lochbaum, A. Dorodnyy, U. Koch, S. M. Koepfli, S. Volk, Y. Fedoryshyn, V. Wood, and J. Leuthold, Nano Lett. **20**, 4169 (2020).
[139]J. Yang, W. Du, Y. Su, Y. Fu, S. Gong, S. He, and Y. Ma, Nat. Commun. **9**, 4033 (2018).
[140]M. S. Mirmoosa, S.-A. Biehs, and C. R. Simovski, Phys. Rev. Appl. **8**, 054020 (2017).
[141]J. DeSutter, L. Tang, and M. Francoeur, Nat. Nanotechnol. **14**, 751 (2019).
[142]A. Fiorino, L. Zhu, D. Thompson, R. Mittapally, P. Reddy, and E. Meyhofer, Nat. Nanotechnol. **13**, 806 (2018).