OPTICAL RESONATORS

Microphotonic thermal imaging

High-performance thermal imaging technology typically involves using cryogenically cooled devices. In the future, detectors based on arrays of tiny optical resonators could lead to sensitive, rapid, thermal imaging at room temperature.

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The advent of high-quality-factor (high-Q) micrometre-scale optical resonators has led to the demonstration of high-fidelity optical sensors. These devices can be used for various types of sensing — mechanical, biological and chemical, for example — and often have far better sensitivity than conventional techniques. Microphotonic resonators could also be useful as uncooled thermal detectors, offering significantly better noise performance, smaller pixel size and faster response times than existing thermal detectors. These advantages make the prospect of a microphotonic thermal imager highly attractive.

Most modern optical imagers are constructed of arrays of photon-detector elements known as focal plane arrays (FPAs). Photon detectors directly generate electron–hole pairs from incident radiation and provide excellent noise performance when the photon energy is much larger than the thermal energy, k_BT (where k_B is Boltzmann's constant and T is temperature). However, for wavelengths longer than a few micrometres, photon detectors have to be cooled, often to cryogenic temperatures, to minimize thermally induced energy-level transitions. Alternatively, FPAs can be formed from thermal detectors, where the incident radiation generates thermal energy and a corresponding temperature shift. This shift is then sensed through a change in some physical characteristic of the detector element, be it mechanical, electrical, optical or otherwise. Although thermal noise is of course still problematic, fluctuations between energy-level states within a thermal detector do not typically degrade performance. The impact of thermal noise is therefore more controllable and room-temperature operation of a thermal detector is possible, independent of the incident photon energy.

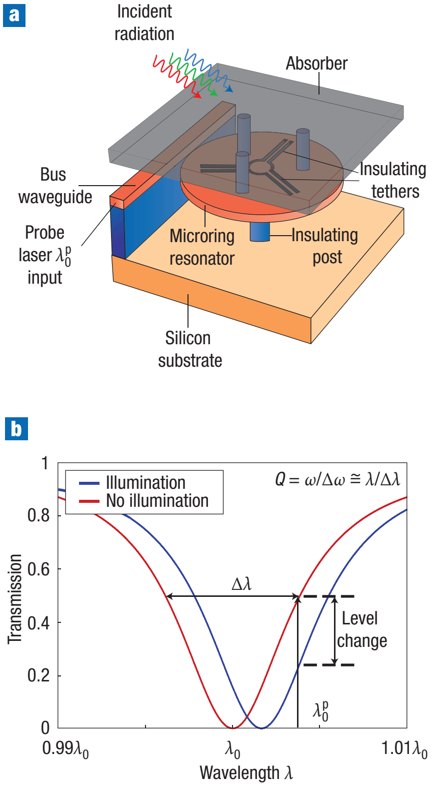

Figure 1 Heat detection using optical resonators. **a**, Schematic of a thermal microphotonic detector. The detector consists of a thermally isolated microphotonic resonator thermally coupled to an absorbing element and evanescently coupled to a bus waveguide. **b**, In its simplest form, the readout consists of a probe laser at the 3-dB point of the resonance. On illumination, the temperature of the microresonator increases, shifting the resonant wavelength by means of the thermo–optic effect, and a change in transmission is detected. (Here, ω is the microring-resonator frequency, λ_0 is the resonant wavelength of the resonator with no illumination and λ_0^p is the probe wavelength.)

The development of microbolometer-based FPAs, which rely on the temperature coefficient of resistance to sense temperature changes, has made it possible for thermal images to be recorded at room temperature. This breakthrough opened up infrared and long-wave imaging to a wide range of applications for which photon detectors do not exist or cryogenic cooling requirements limit their use. Yet, despite over two decades of development, the noise performance of room-temperature microbolometers is inadequate for imaging systems for which the ratio of focal distance to aperture size is substantially greater than one. Moreover, microbolometer array sizes remain smaller than one megapixel with pixels larger than 20 μm, significantly limiting both resolution and field of view. These limitations have spurred on efforts to develop alternative thermal imaging techniques.

One such technique is thermal microphotonic imaging, which involves combining high-Q micrometre-scale resonators with extreme thermal isolation to ensure low-noise thermal detection. However, an FPA-based approach requires the production and integration of millions of such microphotonic elements on one chip, and the integration of an equally scalable readout technique. Here, we review noise sources inherent to thermal detectors, and present an approach for thermal microphotonic detection and one possible readout technique. Our goal is to inspire researchers to consider thermal microphotonic imaging as an approach with the potential to reach levels of performance previously attained only by cryogenically cooled detectors.

NOISE ISSUES

Fundamentally, thermal detectors are limited by thermal phonon fluctuations due to energy exchange with a thermal bath (such as the substrate in the device)[1]. This energy exchange, described by Gibbs[2], is classical in origin (analogous to brownian motion) and cannot be distinguished from absorbed radiation. The resultant noise equivalent power (NEP) of this background phonon flux is given by $\mathrm{NEP}_{\mathrm{phonon}} = \sqrt{4k_BGT}$, where G is the thermal conductance to the substrate. Assuming room-temperature operation, the only free parameter to play with is G. For $G = 10^{-7}$ W K^{-1}, 10^{-8} W K^{-1} and 10^{-9} W K^{-1}, the thermal phonon noise levels are, respectively, $\mathrm{NEP}_{\mathrm{phonon}} = 7 \times 10^{-13}$ W Hz$^{-1/2}$, 2×10^{-13} W Hz$^{-1/2}$ and 7×10^{-14} W Hz$^{-1/2}$. The value $\mathrm{NEP}_{\mathrm{phonon}} = 7 \times 10^{-14}$ W Hz$^{-1/2}$ is in the vicinity of cryogenically cooled photon detectors.

In addition to the unavoidable thermal phonon fluctuations, the resistive elements in bolometers also suffer from temperature fluctuations of the electrons commonly referred to as Johnson noise[3]. Bolometers suffer from noise that scales inversely with incident frequency, resulting from trapped charge and non-ohmic contacts. Furthermore, room-temperature bolometers have a small temperature coefficient of resistance resulting in a small scale factor, or fractional change in signal, for a given amount of absorbed radiation. Finally, microbolometer operation involves a trade-off between achieving low thermal conductance, G, and high electrical conductance, and the best microbolometers currently achieve $G \approx 10^{-7}$ W K^{-1}. The minimum noise levels of a room-temperature microbolometer are given by NEP ≈ 10^{-11} W Hz$^{-1/2}$, which is an order of magnitude higher than the minimum phonon noise levels and two orders of magnitude higher than what might be possible in a more sensitive and thermally isolated room-temperature thermal detector.

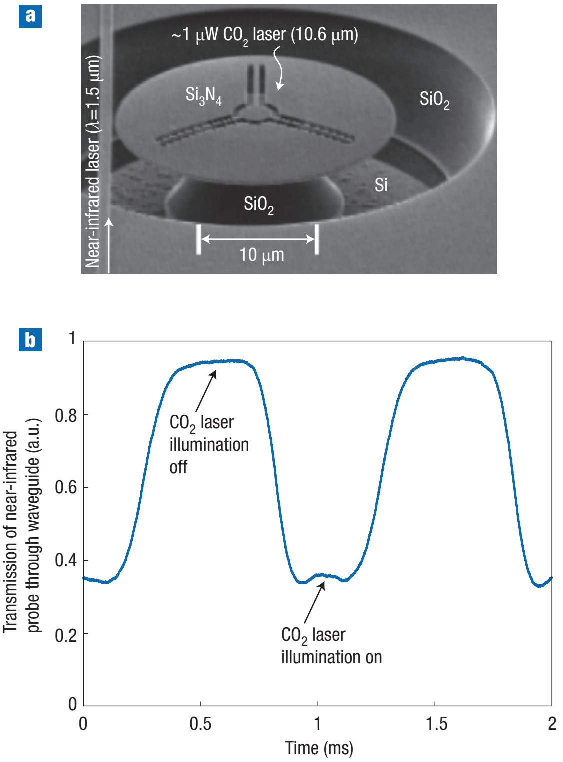

Figure 2 Prototype microphotonic thermal detectors. **a**, Scanning electron micrograph of a representative silicon-nitride-based microphotonic thermal detector. **b**, Response of the microphotonic thermal detector to an on–off modulated (that is, chopped) CO$_2$ laser signal at a wavelength of λ = 10.6 μm and with about 1 μW of incident power. The temperature change resulting from the silicon nitride microphotonic resonator absorbing the carbon dioxide laser light induces a change in the transmission of the near-infrared (λ = 1.5 μm) laser line probing the resonator, as described in Fig. 1b.

THERMAL MICROPHOTONIC DETECTORS

A thermal microphotonic detector consists of a bus waveguide, a thermally isolated microresonator, and an absorbing element in thermal contact with the microresonator (Fig. 1a). The bus waveguide is critically coupled to the microphotonic resonator so as to ensure complete extinction of transmission in the waveguide on resonance. The absorber converts incident optical power to thermal power, causing a rise in temperature in both the absorber and the resonator. For a given absorbed power level, P_{abs}, the temperature rise is P_{abs}/G, where G is the thermal conductance from the resonator to the substrate. This temperature rise shifts the resonance through the thermo–optic effect, as shown in Fig. 1b. The shift can be detected by a laser line operating at one of the 3-dB points of the resonance. The fractional change ΔS in the signal S for a given amount of absorbed power P_{abs} (the so-called scale factor), is given by

$$\frac{\Delta S}{S \cdot P_{abs}} = -\frac{Q}{G}\frac{d\lambda_0}{\lambda_0 dT},$$

where λ_0 is the resonant wavelength (the minus sign is introduced to be consistent with Fig. 1b). Assuming a Q of 10^6 and a thermal conductance of $G = 10^{-7}$ W K^{-1}, cavities made of silicon nitride and silicon have scale factors that are approximately 600 and 2,500 times larger than microbolometers, respectively. This alone is significant, but the advantage is even more substantial considering the fact that there is no need for electrical contacts with the sensor. With only dielectric supports connecting the sensor to the substrate, thermal conductances of $G = 10^{-8}$ W K^{-1} are certainly possible, and $G = 10^{-9}$ W K^{-1} may be realizable, further enhancing the scale factor and reducing the NEP of the thermal fluctuations. In addition to the significant advantages of scale factor and greater thermal isolation, microphotonic detectors do not suffer from Johnson noise in the sensing element. They do not have significant noise components that scale inversely with frequency, and with the use of linear media, the probe signal does not perturb the sensor. All of these traits point to the potential of measuring thermal fluctuations two orders of magnitude below those detectable by microbolometers at present. In addition, by using high-refractive-index-contrast materials, pixel sizes can be reduced to about 5 μm, which not only enhances resolution but also improves the thermal response for high-speed applications.

PROTOTYPE TESTING

Prototype microphotonic detectors have been designed and fabricated. A scanning electron micrograph of a detector made of silicon nitride and supported by an oxide post and silicon nitride tethers is presented in Fig. 2a. The response to incident, 10.6-μm-wavelength radiation was obtained by probing the 3-dB point of the resonance with a near-infrared laser (λ = 1.5 μm) and illuminating the microphotonic resonator with approximately 1 μW of power from a carbon dioxide laser. The response is shown in Fig. 2b. The set-up exploits the inherent strong absorption of silicon nitride at wavelengths of λ = 9–13 μm and the transparency of silicon nitride to the near-infrared probe laser. Although

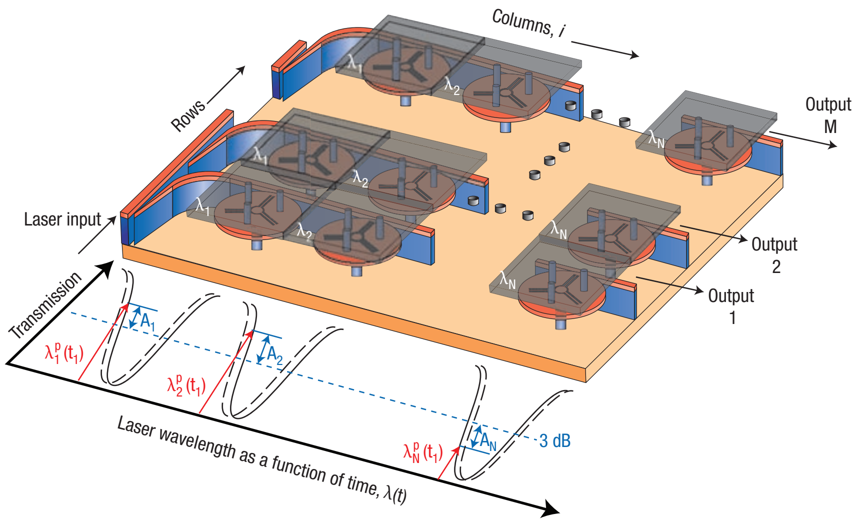

Figure 3 Concept for a TM-FPA. The TM-FPA approach depicted uses a WDM-based readout technique to probe columns of sensors. The resonances can be probed by simply stepping the laser to a 3-dB point of the initial centre wavelength of each column and reading out the amplitudes of transmission. This concept is just one possibility, and alternative approaches with greater linearity and dynamic range exist.

functional, the thin (200-nm-thick) silicon nitride microresonator absorbs less than 10% of the incident thermal radiation. Moreover, the thermal conductance to the substrate is limited to about $G = 10^{-6}$ W K^{-1} owing to conduction through air. Notably, constraints on the initial fabrication limited the microresonator quality factors to only $Q = 10^4$. So, although basic functionality has been demonstrated, direct competition with microbolometers will require integrated absorbers, vacuum packaging and enhanced resonator quality factors.

SCALING UP TO AN ARRAY

Scaling up from a single prototype sensor to a working thermal microphotonic FPA (TM-FPA) will certainly require significant effort. Principal among the challenges is the requirement for a scalable and reliable readout approach. At least two readout techniques for the microphotonic pixels can be envisioned. First, pixels could be switched using microelectromechanical-system (MEMS)-based elements. Alternatively, a wavelength-division multiplexing (WDM) approach could be used. Wavelength-division multiplexing is attractive because it does not significantly burden the already complex fabrication process. A variety of WDM methods can be used to probe the microphotonic resonances, but for consistency we consider the approach of measuring the amplitude of transmission, shown in Fig. 1b and Fig. 2b and replicated for an array in Fig. 3.

Each column of pixels is fabricated to have its own distinct resonant wavelength. A laser input is sent to each row to enable simultaneous readout of the pixels within the column. The laser wavelength is then scanned or stepped across all of the centre wavelengths in the array. For this approach, the probe wavelength λ_i^p is stepped to a 3-dB point of a pixel column, *i*. As each pixel in the column will have a resonant wavelength that has been altered slightly by the absorbed radiation, the transmission of each will differ and the detected amplitude of transmission for each pixel will then indicate the relative power absorbed. In this manner, each column is addressed and read out. To implement a megapixel array, one thousand wavelengths would need to be addressable. Excess coupling losses to the microrings would need to be exceedingly small (about 0.01 dB) and control over the resonant wavelengths of the microrings would have to be precise.

Fabricating a million or more suspended microphotonic resonators with low loss and precise (picometre-level) wavelength control will be an equally significant challenge. However, it is important to point out that the prototype sensors (Fig. 2a) were fabricated on a CMOS production line using MEMS techniques for microfabrication that have a proven record of scalability. Moreover, no exotic materials are required to implement a TM-FPA, and interestingly, no electronics need be implemented on-chip. The chip can be entirely passive.

FUTURE OUTLOOK

Challenging an established technology is inherently difficult. Unforeseen advances in microbolometer or alternative room-temperature thermal imaging techniques could negate the efforts being made at present to develop microphotonic thermal imaging technology. Still, the seemingly clear advantages of microphotonic thermal detection, in terms of scale factor, thermal noise levels, pixel size and response time, make a compelling case for the development of single-detector elements. Scaling up to an array of detector elements with a million or more components presents many additional challenges, but if addressed, significantly improved room-temperature thermal imaging is expected to result. Finally, it is worth pointing out that few applications require scaling comparable to that of an FPA. Thermal microphotonic detection and a TM-FPA have the potential to drive very-large-scale integrated microphotonics to a level perhaps not previously envisioned.

References

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Acknowledgements

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