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Nanophotonic AFM Transducers Enable Chemical Composition and Thermal Conductivity Measurements at the Nanoscale

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Abstract

The atomic force microscope (AFM) offers a rich observation window on the nanoscale, yet many dynamic phenomena are too fast and too weak for direct AFM detection. Integrated cavity-optomechanics is revolutionizing micromechanical sensing; however, it has not yet impacted AFM. Here, we make a groundbreaking advance by fabricating picogram-scale probes integrated with photonic resonators, to realize functional AFM detection that achieve high temporal resolution (< 10 ns) and picometer vertical displacement uncertainty, simultaneously. The ability to capture fast events with high precision is leveraged to measure the thermal conductivity (η), for the first time, concurrently with chemical composition at the nanoscale in photothermal induced resonance experiments. The intrinsic η of metal-organic-framework individual microcrystals, not measurable by macroscale techniques, is obtained with a small measurement uncertainty (8 %). The improved sensitivity (50 $\times$) increases the measurement throughput 2500-fold and enables chemical composition measurement of molecular-monolayer-thin samples. Our paradigm-shifting photonic readout for small probes breaks the common tradeoff between AFM measurement precision and ability to capture transient events, thus transforming the ability to observe nanoscale dynamics in materials.

TOC image

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Supporting Information

Methods Section including: transducers fabrication, sample preparation, data fitting procedure, supplementary discussions (SD1–7), Figures. S1 to S6, Tables S1 and S2.

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Keywords

Optomechanical Resonators; PTIR; Thermal Conductivity; Chemical Composition; Nanoscale Dynamics; AFM

The atomic force microscope (AFM) enables progress in material science,^{1, 2} biology,³ and other fields, by detecting morphological, chemical,^{4, 5} mechanical,^{3, 6} thermal,^{7, 8} electrical,⁹ optical,¹⁰ and other properties with nanoscale resolution. Considerable efforts are directed towards improving AFM detection bandwidth and sensitivity to increase throughput, the ability to detect small signals, and to capture dynamic events such as protein folding³, heat diffusion¹¹ and others⁶ at progressively shorter time scales. Reduction of the probe mass enables faster response and widens the detection bandwidth; reduction of size lowers dissipation and force noise from fluid drag. However, because far-field optical detection becomes inefficient for probes with cross-sections below the diffraction limit,¹² rapid and low-noise motion detection for very small probes is challenging and curbs the benefits of probe miniaturization. Cavity-optomechanics is revolutionizing micromechanical sensing^{13–15} in many applications, and has been proposed for realizing an AFM sensor.¹⁵ However high-performance AFM measurements based on cavity-optomechanics have not been demonstrated, until now, due to the serious microfabrication challenges that must be overcome to transition from simplified demonstrative devices¹⁵ to fully-integrated, functional AFM probes.

Leveraging dynamic signal detection, photothermal induced resonance (PTIR)^{2, 4, 5, 16} combines the spatial resolution of AFM with the specificity of absorption spectroscopy (Fig. 1A). In PTIR, when the sample absorbs a light pulse it heats up and expands inducing vibrations in the AFM cantilever (like a struck tuning fork) with amplitudes directly proportional to the absorption coefficient of the sample.¹⁷ Notably, the proportionality of the PTIR signal to the energy absorbed by the sample,^{17, 18} as in conventional infrared (IR) spectroscopy, allows material identification by comparison with far-field IR spectral databases.¹⁶ PTIR also enables conformational analysis⁴, mapping of composition¹⁹, and bandgap²⁰ at the nanoscale. Although conventional cantilevers adequately capture the light absorption magnitude, they lack the speed and motion-detection precision for tracking the sample thermal expansion dynamics to extract its local thermal conductivity (η).¹¹

In this work, an integrated near-field cavity-optomechanics readout concept¹⁵ is implemented, for the first time, to realize fully-functional nanoscale AFM probes capable of ultralow detection noise ($\approx 3 \text{ fm}\cdot\text{Hz}^{-0.5}$) within an extremely wide measurement bandwidth ($> 25 \text{ MHz}$) in ambient conditions, surpassing all previous AFM probes. This advance

allows capturing previously inaccessible PTIR time-domain thermal expansion dynamics with high temporal resolution (<10 ns) and low noise (<1 pm per point), while simultaneously improving the PTIR signal-to-noise ratio (SNR). The low probe mass yields high quality nanoscale IR spectra even from thin (< 2 nm) samples. The high temporal resolution ($\approx 1500\times$ -faster than temperature-sensitive probes, see supplemental discussion – SD 1)¹¹ enables accurate evaluation of the thermal conductivity from samples that are too small, heterogeneous at the nano-scale and/or difficult to prepare for micro- and macro-scale techniques.²¹ This new method is validated by analyzing polymethyl-methacrylate (PMMA) thin films with well-known characteristics, and later applied to measure the thermal conductivity of metal-organic framework (MOF)^{22, 23} microcrystals of unknown η . MOFs are a class of nanoporous materials promising in catalysis, gas storage, sensing and separations. Accurate knowledge of the thermal conductivity is crucial to engineering MOFs for these applications, and for novel MOF-based thermoelectric devices; however, η has been measured only for a few MOFs.^{24, 25} Because these materials are typically obtained as microcrystalline powders, macroscale thermal conductivity measurements are affected by the crystals packing density and do not provide the intrinsic η . The development of an ultrasensitive near-field optical motion readout of a fast and ultralight (≈ 1.2 pg) AFM transducer probe is the key revolutionary advance that allows measurement of the intrinsic thermal conductivity of MOFs crystals presented here, and of other nanomaterials.

Here, a fiber-pigtailed optomechanical transducer chip (hereafter transducer), was integrated into a modified commercial PTIR setup²⁶ using a custom 3D-printed adaptor, replacing the conventional AFM cantilever. The transducer (Fig. 1C,E), consists of a picogram-scale mechanical probe wrapped around a stationary microdisk optical resonator cavity implementing high quality-factor (Q) interferometric motion readout. The nominally 100 nm to 200 nm wide, 20 μ m long mechanical probe and 10 μ m diameter microdisk were nanofabricated from a ≈ 260 -nm thick single-crystal Si layer (details available in the supporting information, SI). A 500-nm-wide on-chip Si waveguide is evanescently coupled to the cavity, and connected via optical fibers to a continuous-wave tunable laser (1520 nm – 1570 nm) and to a photoreceiver, replacing the AFM laser beam-bounce detection (Fig 1C). The evanescent fields of the disk whispering-gallery optical modes provide optomechanical coupling between the probe and the disk across a small air-gap (≈ 150 nm). Each of the disk's optical resonances ($15000 < Q < 100000$) manifests as a dip in the transducer's transmission spectrum (see Fig 1F), and shifts sharply and proportionally to the probe displacement (typical optomechanical coupling $g_{OM}/2\pi \approx 0.5$ GHz/nm). In operation, the laser wavelength is fixed at the steepest slope point on the resonance side such that probe motion modulates the transmitted light intensity, yielding the AFM “deflection signal”.

In PTIR, a wavelength-tunable pulsed (≈ 10 ns) laser illuminates the sample and an AFM tip contacting the sample serves as local detector (Fig 1A,C). The absorbed (mid-IR) light excites vibrational modes localized on specific chemical groups, converting optical energy into vibrational energy. Within < 1 ns, the vibrational energy is redistributed to lower-energy modes and transferred to phonons, which transport the heat.²⁶ The consequent rapid sample thermal expansion displaces the AFM tip and excites one or more cantilever oscillation modes. The probe motion is measured by reflecting a laser beam off a conventional cantilever towards a position-sensitive detector (Fig 1A) or by measuring the transmitted-

light intensity using the transducers (Fig 1C). In our setup, the photodetector output from the transducer is digitized with a fast oscilloscope (500 MHz sampling rate) to capture the time-domain PTIR signal with high temporal resolution. The oscilloscope traces were saved and analyzed offline to gain access to the sample thermal expansion dynamics (see below). Simultaneously, the same signal, buffered by the oscilloscope preamplifier, was fed into the commercial PTIR system where it was separately digitized (50 MHz sampling rate). To reduce the noise introduced by the commercial digitizer the signal was filtered by a broad band-pass FFT filter (≈ 3.7 MHz bandwidth) around the transducer resonant frequency (≈ 10 MHz). IR spectra and maps were generated by the commercial PTIR software that determines the peak-to-peak amplitude (maximum minus minimum intensity) of the filtered PTIR time-domain signal trace; which is proportional to the absorbed energy.^{17, 18} When using conventional cantilevers the FFT filter had a bandwidth of 100 kHz centered at the cantilever second mechanical resonance (≈ 200 kHz).

Fig 2A–C shows the topography, PTIR maps and spectra obtained using the transducer on a chemically heterogeneous polymer sample demonstrating chemical imaging with high spatial resolution, similarly to previous PTIR experiments using conventional cantilevers.¹⁸

Generally, the PTIR signal (S) is a sum of up to 3 terms:

$$S = S_{osc} + S_{exp} + S_{bkg}. \quad (1)$$

Here S_{osc} describes the ring-down dynamics of the cantilever mechanical oscillations. For a fast probe, S_{exp} additionally describes the probe's motion, tracking directly the fast sample thermal expansion and slower contraction. S_{bkg} describes any contribution to the output signal that is not mechanical in nature (background). S_{osc} is the only measurable signal with conventional cantilevers (Fig 1B) or with the transducers on samples with fast thermalization dynamics (Fig 2D). Only the first transducer contact-mode (≈ 10 MHz, Fig. 1G) contributes to S_{osc} , because the faster, higher-order modes adiabatically follow the ≈ 10 ns sample thermal expansion.

The transducers allow measuring PTIR spectra of a ≈ 2 nm thick Octadecylchlorosilane (OTS) monolayer (Fig. 2E, fig S1) with high SNR (≈ 174) and in good agreement with macroscale FTIR spectra.²⁷ Remarkably, although OTS has only one CH_3 group per molecule, its spectrum clearly shows the CH_3 antisymmetric-stretching peak (2962 cm^{-1}). For such a thin sample, the laser pulse and the sample thermalization (< 1 ns), are much faster than the oscillation period for either the transducer (≈ 10 MHz) or a conventional cantilever (≈ 200 kHz) contact modes frequencies. Because in this regime the oscillation amplitude excited by the impulsive sample expansion is proportional to the mode's resonance frequency (see supplemental discussion SD-2), the transducers provide $\approx 50\times$ -larger mechanical amplitude. For a sufficiently low-noise motion readout, such as in the case of our transducers (Figure 1G), the measurement SNR is determined by the cantilever amplitude response relative to the cantilever thermal motion noise ($\langle x^2 \rangle = K_B T / k$ per equipartition theorem, where K_B is the Boltzmann constant, T is the temperature, k is the cantilever stiffness and x is the cantilever motion). Because conventional cantilevers and the

transducers have comparable stiffness, the larger signal amplitude of the transducers results in a 50x-larger SNR (Fig. 1D) than for conventional cantilevers (Fig 1B) when measuring the same sample (i.e. 50 nm thick PMMA in Fig. 1) under identical experimental conditions (sample location power, polarization, wavelength, averages).

Using conventional cantilevers, an additional Q -fold mechanical gain is obtained with the resonance-enhanced PTIR technique,⁵ by resonantly exciting a cantilever mode at the resonance frequency f . In contrast, the transducer's high gain is intrinsic, that is independent of Q and f (or weakly dependent on f near resonance in the case of samples with short-lived thermal expansion, see SD-2). Therefore, the transducer PTIR measurement is largely immune to possible artefacts induced by modest changes in f and Q due to spatially-varying stiffness and damping at the probe-sample contact point.

In PTIR, the measurement uncertainty is determined by the sum of the probe and optical readout input-referred displacement noise power. Reduction of the probe's cross-section to the nanoscale strongly reduces air-drag and the corresponding thermodynamic force noise-spectral-density, which lowers the displacement noise-density at all frequencies away from the probe resonance. The input-referred noise of the optomechanical readout is not only much smaller than the displacement noise near the resonance, but more importantly, it approaches the probe displacement noise *at all frequencies below resonance* (Fig. 1D, see SD-3). The large bandwidth and low noise of our transducers are ideal for directly measuring fast time-domain sample surface motion (Fig. 3).

The thermal-expansion dynamics of the sample surface is influenced by the η which governs the heat diffusion within the sample. Consequently, the local η can be extracted from the S_{exp} term of the PTIR signal, leveraging a suitable thermo-mechanical model. Thermoreflectance experiments²¹ that also evaluate η by measuring surface motion, typically rely upon finite-element method calculations of the heat diffusion in the sample and substrate. However, we find (see SD-4) that for an impulsive excitation and for a substrate with high thermal conductivity (i.e. heat-sink at constant temperature) the sample temperature and thermal expansion are well described by an instantaneous rise followed by a single exponential relaxation $\propto e^{-t/\tau_s}$, where τ_s is the time constant of the slowest (fundamental) thermal mode. This simplified, yet acceptably accurate model enables analytical calculation of S_{exp} , thereby potentially allowing near real-time data analysis and η -mapping. Because the phonon mean free path in PMMA is below 1 nm,²⁸ and well below the sample thickness analyzed in this work, no ballistic heat transport is considered in our model.

With these assumptions, the contributions to the PTIR signal are (see SD-5 and SD-6):

$$S_{osc} = \frac{A \cdot e^{-\frac{\pi f t}{Q}}}{2 \left[1 + \left(\frac{1}{2\pi f \tau_s} - \frac{1}{2Q} \right)^2 \right]} \cdot \left(-\cos(2\pi f t) + \left(\frac{1}{2\pi f \tau_s} - \frac{1}{2Q} \right) \cdot \sin(2\pi f t) \right) \quad (2)$$

$$S_{\text{exp}} = A \cdot \left[r - \frac{1}{2} \frac{\left(\frac{1}{2\pi f \tau_s} - \frac{1}{2Q} \right)^2}{1 + \left(\frac{1}{2\pi f \tau_s} - \frac{1}{2Q} \right)^2} \right] \cdot e^{-\frac{t}{\tau_s}} \quad (3)$$

$$S_{\text{bkg}} = B x_t \int_0^t \exp\left(-\frac{v}{\tau_s}\right) (t-v)^{-3/2} \exp\left(\frac{x_t^2}{4\alpha(t-v)}\right) dv \quad (4)$$

where t is the time, τ_s is the sample thermalization time, A , f and Q are the amplitude, frequency and Q -factor of the probe oscillation mode, respectively. r is the ratio of DC to AC amplitudes of the optically read-out cantilever response to a step-function. S_{bkg} in our experiments (see SD-6) arises from non-local through-air heat transfer from the hot sample surface, which shifts the optical resonance via the thermo-optic effect. Eq.4 describes the expected time-dependent air temperature change at distance x_t from the sample surface, whose temperature decays exponentially after a fast raise. If used as independently adjustable parameters, data fitting returns the expected values for the air thermal diffusivity (α) and surface-disk distance x_t . Similarly, the r from the fit agrees with an independent calculation from the probe parameters (see SD-5). Notably, S_{osc} , S_{bkg} and S_{exp} have different time scales (Fig. 3A,B) and are well separated in the frequency domain, facilitating the fit and a robust parameter estimation. S_{osc} is centered near the ≈ 10 MHz probe frequency ($\tau_{\text{osc}} = 1/(2\pi f) = 16$ ns), S_{exp} has a relaxation time $40 \text{ ns} < \tau_s < 1700 \text{ ns}$ for the samples analyzed here, and the S_{bkg} peaks at about $2 \mu\text{s}$.

In the absence of interfacial thermal resistance (R), τ_s is given by¹¹ (see SD-7):

$$\tau_s = \frac{4}{\pi^2} \cdot \frac{C_p \cdot \rho \cdot z^2}{\eta} = \frac{4}{\pi^2} \cdot \frac{z^2}{D} \quad (5)$$

where C_p is the specific heat capacity, ρ is the density, $D = \eta/(C_p \cdot \rho)$ is the thermal diffusivity and z is the sample thickness. Measuring z and τ_s allows determination of the local D , or η , when C_p and ρ are known. For finite R , τ_s satisfies

$$\begin{cases} \tau = \frac{C_p \rho}{\eta} l_0^2 \tan^2 \xi \\ l_0 \xi \tan \xi = z \end{cases} \quad (6)$$

where $R_0 \equiv \eta/R$ (SD-7). In the limit of small R , $R_0 \ll z$, $\xi \rightarrow \frac{\pi}{2}$, leading to eq. 5.

The τ_s values measured on a PMMA wedge sample ($15 \text{ nm} < z < 600 \text{ nm}$) follow approximately the expected z^2 -dependence (Fig 3C), while plotting

$\eta_{eff}(z) \equiv \frac{4}{\pi^2} \cdot \frac{C_p \cdot \rho \cdot z^2}{\tau_s(z)}$ (Fig. 3D) qualitatively highlights the effect of the interfacial thermal resistance (for negligible R , η_{eff} would be z -independent). The τ_s uncertainty represents a single standard deviation of repeat measurements obtained on distinct locations of the same thickness and with different instrumental parameters such as excitation wavelength and pulse energy. Leveraging known values for C_p and ρ (Table S1) and using η and R as adjustable parameters, an error-weighted implicit fit of (6), (fig 2C, D) yields $\eta = 0.178 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1} \pm 0.014 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$. The acquisition-time per point ($\approx 2 \text{ s}$) and the nanoscale η uncertainty ($\approx 8 \%$) compare favorably with the acquisition time and uncertainty of state-of-the-art thermo-reflectance measurements^{21, 29} with micron-scale spatial resolution.

Having validated our model on PMMA, we next measure HKUST-1³⁰ microcrystals (Fig 4) obtained directly on the ZnSe prism by adapting an ink-jet printing method³¹. The measured $\tau_s(z)$ values are well described by equation 5 (Fig 4C) and using HKUST-1 known C_p and ρ (table S1) we estimate $\eta^{HKUST-1} = 0.26 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1} \pm 0.02 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ at $RH = 1.8 \%$ $\pm 0.3 \%$ (Fig. 4D). In contrast to steady-state measurements reporting a negative thermal-expansion coefficient for HKUST-1,³² our technique directly measures a positive expansion at short time scales ($< 1 \mu\text{s}$). This new observation highlights the complexity of the thermo-mechanical behavior in these materials, and may foster a better understanding of their fundamental properties.

In summary, the very large bandwidth and SNR of the picogram cavity-optomechanical probes open AFM access to fast dynamic processes at the nanoscale. This advanced transduction technique enables detection of chemically-specific IR absorption of short laser pulses by monolayer-thick films in PTIR, increasing sensitivity by almost two orders of magnitude. Furthermore, it also provides direct access to fast sample thermalization dynamics in the time domain enabling concurrent measurements of chemical composition and thermal properties at the nanoscale. Because PTIR allows material identification, informing on ρ and C_p via literature data, we reason that this method can provide η for samples and impurities whose composition is initially unknown. While the $50\times$ PTIR signal-to-noise ratio improvement decreases the need for averaging 2500-fold, the transducers also relax back to equilibrium after each pulse 100-times faster ($\approx 5 \mu\text{s}$, Fig 1D) than conventional cantilevers ($> 500 \mu\text{s}$, Fig 1B) and leveraging high (200 kHz) repetition rate lasers⁵, could further improve the PTIR throughput 200-fold (see SD-8).

Because many nanomaterials consist of nanoparticles or microcrystals that are too small or heterogeneous for macro-scale thermal conductivity measurements, we believe that the method presented here will foster the development of nanomaterials in thermoelectric, electronic and other applications. Furthermore, we believe that the transducers' low drag cross-section (see SD-3) will open new opportunities for nanoscale chemical imaging in liquids with a future broad impact in biology, medicine, and materials science.

PTIR SETUP AND MEASUREMENTS

PTIR experiments were obtained using a modified commercial PTIR instrument. The set up used in this work consists of a contact mode atomic force microscope (AFM) interfaced with wavelength-tunable pulsed laser sources (laser A and B), as described previously.³³ Laser A consists of an optical parametric oscillator based on a noncritically phase-matched ZnGeP₂ crystal that emits 10 ns long pulses ($\approx 10 \text{ cm}^{-1}$ linewidth) at 1 kHz repetition rate in the spectral range from 4000 cm^{-1} to $\approx 1025 \text{ cm}^{-1}$ (from $2.5 \mu\text{m}$ to $9.76 \mu\text{m}$). Laser B consists of a synchronously pumped difference frequency generation laser system emitting $\approx 100 \text{ ps}$ long pulses with a 0.5 cm^{-1} linewidth at 1 kHz repetition rate. Laser B wavelength is nominally tunable between 6450 cm^{-1} ($1.55 \mu\text{m}$) to 625 cm^{-1} ($16.00 \mu\text{m}$). Laser A and B emit linearly polarized light. Because the laser power at the sample was controlled with a wire grid polarizer, the light polarization at the sample is also affected by the polarizer's settings. In each experiment the light polarization at the sample was linearly polarized and constant, but the polarization state was not deliberately controlled and may have varied between experiments, unless otherwise noted.

Conventional PTIR measurements were obtained by reflecting the AFM laser beam off $450 \mu\text{m}$ long conventional Si contact-mode AFM probes (nominal spring constant between 0.07 N/m and 0.4 N/m) onto a 4-quadrant AFM detector (see Fig 1A).

PTIR measurements with the optomechanical transducers (see Fig 1C of the main text) were obtained by mounting the transducer chip on a custom AFM head using a 3D-printed stainless steel adaptor. The detection scheme (Fig 5) consists of a fiber coupled continuous wave (CW) tunable laser ($1520 \text{ nm} - 1570 \text{ nm}$), an optical isolator, a variable optical attenuator, a fiber polarization controller, the transducer and a room-temperature InGaAs photoreceiver (DC coupled, 3 dB bandwidth of 125 MHz).

The signal from the photoreceiver is used to provide both the vertical deflection signal for the AFM, and PTIR signal ($S = S_{osc} + S_{exp} + S_{bkg}$). To provide the AFM feedback, the signal is low pass filtered and amplified (1-fold to 5-fold) and then fed to the vertical deflection input channel of the commercial PTIR system. To record and analyze the fast thermal expansion dynamics of the sample, the photodetector output is digitized with a fast oscilloscope (11 bit) at a sampling rate of 500 MHz. Oscilloscope traces of the time-domain PTIR signal were saved and analyzed offline as described in the main text. The preamplifier circuit of the oscilloscope is also used to buffer the signal before feeding it to a fast input channel (50 MHz sampling rate) of the commercial PTIR system. This scheme allows to perform in depth offline analysis of the fast probe dynamics (oscilloscope traces) as well as to use the digitizing electronics, algorithms and software of the commercially available PTIR system for PTIR spectral acquisition and imaging. The PTIR spectra and maps were obtained using the commercial software of the PTIR instrument, recording the peak-to-peak amplitude of the oscillatory term (S_{osc}), which is proportional to the absorbed energy.^{17, 18}

Spectra were obtained by averaging the response traces from 256 laser pulses at each wavelength and by sweeping the wavelength at 4 cm^{-1} intervals. PTIR images were recorded by illuminating the sample with a constant wavelength while scanning the sample.

The *SNR* of the PTIR traces in Fig 1B and Fig 1D was obtained by dividing the PTIR peak to peak signal (maximum minus minimum intensity of the time-domain trace) by the peak to peak noise obtained after the completion of the cantilever ringdown. The AFM height and the PTIR signal acquisition was synchronized so that for each pixel the PTIR signal was an average over 32 laser pulses. The pixel sizes are 100 nm × 100 nm in all images.

The oscilloscope PTIR traces used to evaluate the sample thermal conductivity were obtained by averaging typically 2048 individual pulse responses, which provide a typical statistical uncertainty of < 1 pm per point when sampled at 10 ns per point (averaging 5 sequential points recorded at 500 MHz sampling rate), as detailed in supplemental discussion 3.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1. Nanophotonic optomechanical transducers enable large-bandwidth, low noise PTIR measurements

(A) Conventional PTIR: a wavelength-tunable pulsed laser (red) excites the sample in total internal reflection. Following the absorption of a laser pulse, the sample rapidly expands and excites the oscillation modes of an AFM cantilever. The oscillation amplitude (peak to peak) is proportional to the absorbed energy, enabling nanoscale IR spectroscopy; however, the SNR and bandwidth of conventional AFM cantilevers are insufficient for capturing the fast sample thermal expansion and thermalization dynamics. (B) Conventional cantilever PTIR signal for a thin, 50 nm PMMA film. (C) Photonic transducer PTIR: a fiber-pigtailed, integrated transducer leverages cavity-optomechanics to measure motion of a nanoscale probe, radically reducing the noise and increasing the measurement bandwidth for capturing the sample's fast thermalization dynamics induced by laser pulses. (D) The opto-mechanical transducer improves the PTIR SNR by ≈ 50 for a 50 nm PMMA film under the same conditions of panel B (1160 cm^{-1} , 256 pulses averaged). (E) Transducer's colorized scanning-electron micrograph: a nanoscale Si probe is near-field coupled across a nanoscale gap to high- Q whispering-gallery optical modes of a Si microdisk optical cavity. The cavity is evanescently coupled to an integrated waveguide. (F) During the measurement the fiber-coupled laser wavelength (λ_0) is fixed; the sample expansion reduces the cantilever-disk gap, shifting the resonance to longer wavelengths and increases the transmitted intensity (I)

proportionally to the displacement. The measured spectrum before the laser pulse (black) is shifted 15 pm (blue), illustrating a sample thermal expansion of ≈ 3.75 nm. **(G)** The transducer provides an ultralow input-referred measurement noise spectral density (blue) across a wide (25 MHz) bandwidth; integrated over the full bandwidth, the probe thermodynamic noise (black line) slightly exceeds the detection noise (red). (see SD3).

Fig. 2. The transducers enable IR spectroscopy and mapping with high sensitivity and resolution (A) AFM topography and (B) PTIR (1720 cm⁻¹, 3030 cm⁻¹) composition overlay maps of a PMMA (light blue) and polystyrene (red) particles in epoxy matrix (pink). (C) PTIR spectra from marked positions in panel A. (D) PTIR transducer signal and (E) spectrum of an OTS monolayer. The red trace and blue shaded-area are the average of 12-spectra from different sample locations and its 95 % confidence uncertainty. Because of the fast OTS thermalization $S \approx S_{osc}$.

Fig. 3. The transducers enable measuring PMMA thermal conductivity

(A) Transducer signal (1236 cm^{-1}) for 66 nm thick and (B) 598 nm thick PMMA. (C) PMMA thermalization time as a function of thickness; the black line is the best fit given by Eq. 6. (D) PMMA effective thermal conductivity (η_{eff}) as a function of thickness, line based on the Eq. 6 fit to measured τ_s .

Fig. 4. HKUST-1 metal organic framework microcrystals thermal conductivity measurement (A) AFM topography image of MOF microcrystals. (B) Transducer signal (1388 cm^{-1}) for 560 nm thick HKUST-1 microcrystal (x-label in panel A) showing positive thermal expansion (red). (C) thermalization time as a function of thickness; the black line is given by eq. 5. (D) HKUST-1 MOF thermal conductivity as a function of thickness.

Fig. 5. PTIR measurement schematic with the transducers

Optics and electronics schematic that enable the integration of the optomechanical transducer probes with a commercial PTIR system. CWL: CW tunable diode laser, OI: optical isolator, VOA: variable optical attenuator, PC: polarization controller, PD: photo-detector, LP: low-pass filter, AMP: electronic amplifier, SA: spectrum analyzer (used for tip diagnostics and noise spectral density measurement), OS: high-speed oscilloscope, OPO: wavelength-tunable OPO pulsed laser source. Fiber based optical connections are drawn in

blue, integrated waveguide structures are purple, electrical connections are black, free space optical beams are drawn in red.