Nanoscale and Microscale Thermophysical Engineering

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/umte20

Thermomechanical Sensitivity of Microcantilevers in the Mid-Infrared Spectral Region

B. Kwon a, C. Wang a, K. Park b, R. Bhargava c & W. P. King a

a Department of Mechanical Science and Engineering, University of Illinois Urbana-Champaign, Urbana, Illinois
b Department of Mechanical, Industrial and Systems Engineering, University of Rhode Island, Kingston, Rhode Island
c Department of Bioengineering, University of Illinois Urbana-Champaign, Urbana, Illinois

Published online: 13 Feb 2011.

To cite this article: B. Kwon, C. Wang, K. Park, R. Bhargava & W. P. King (2011) Thermomechanical Sensitivity of Microcantilevers in the Mid-Infrared Spectral Region, Nanoscale and Microscale Thermophysical Engineering, 15:1, 16-27, DOI: 10.1080/15567265.2010.502925

To link to this article: http://dx.doi.org/10.1080/15567265.2010.502925

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the “Content”) contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms &
THERMOMECHANICAL SENSITIVITY OF MICROCANTILEVERS IN THE MID-INFRARED SPECTRAL REGION

B. Kwon¹, C. Wang¹, K. Park², R. Bhargava³, and W. P. King¹

¹Department of Mechanical Science and Engineering, University of Illinois Urbana–Champaign, Urbana, Illinois
²Department of Mechanical, Industrial and Systems Engineering, University of Rhode Island, Kingston, Rhode Island
³Department of Bioengineering, University of Illinois Urbana–Champaign, Urbana, Illinois

This article reports the thermomechanical sensitivity of bimaterial cantilevers over a mid-infrared (IR) spectral range (5–10 µm) that is critical both for chemical analyses via vibrational spectroscopy and for direct thermal detection in the 300–700 K range. A physics-based model of cantilever bending was developed by including heat transfer to and within the cantilever, temperature-dependent cantilever bending, and cantilever and optical system IR characteristics. Detailed measurements of the optical system IR characteristics were used as inputs to the model, including Fourier transform infrared (FT-IR) spectral characterization of cantilever absorbance as well as characterization of the light source and monochromator. Mechanical bending sensitivity and noise were modeled and measured for six commercially available microcantilevers, which consist of either an aluminum film on a silicon cantilever or a gold film on a silicon nitride cantilever. The spectral sensitivity of each cantilever was measured by recording cantilever deflection when illuminated with IR light from a monochromator. Predictions of cantilever bending sensitivity and noise compare very well with measurements over the entire spectral range with no fitting parameters or normalization. The results are used to rank the cantilevers for their potential use in IR measurements.

KEY WORDS: bimaterial, microcantilevers, infrared, thermomechanical, photothermal, FT-IR microscopy, monochromator, modeling

INTRODUCTION

The bending of a bilayered or multilayered cantilever can be used to measure small temperature changes or heat flows [1, 2]. Infrared (IR) measurements with bimaterial microcantilevers have shown a temperature sensitivity down to 10⁻⁵ K and heat flow measurements as small as 10 fJ [3, 4]. These thermal characteristics can be used to analyze the properties of samples down to nanogram quantities, compared to milligrams or larger in conventional instruments [5]. Applications of microcantilevers for IR measurements also
include chemical detection using vibrational spectroscopic response of materials; for example, in pharmaceuticals analysis [6, 7]. IR measurements using microcantilevers can offer satisfactory room temperature signal-to-noise characteristics and do not require cryogenic cooling [4]. Further, the intrinsically small sampling volume and commercial availability of cantilevers makes them very attractive as detectors for measuring spectra from microscopic regions.

Published research on IR spectroscopy using bimaterial microcantilevers has reported measurements on biological species [5, 6, 8], chemicals [3, 9], and explosives [7, 10]. Though offering impressive potential for this technology, the quality of spectroscopic data lags traditional IR microspectroscopic methods [11]. Further, the match has not been excellent between cantilever-measured spectra and spectra measured using conventional microspectroscopies. Often some spectral peaks are missing or relative peak intensities were not identical. This discordance is undesirable, because a good match between measured spectra and reference library spectra is typically required for analytical chemical measurements. In general, the literature on microcantilever IR sensing assumes that the cantilever is grey and that the optical system is grey or black. The lack of characterization of the absorbivity and reflectivity properties for microcantilevers thus limits their use for IR spectroscopy. To our knowledge, there are no published reports on determining the IR spectral characteristics of microcantilevers. To overcome this challenge, it is important to understand the IR spectral response of microcantilevers, which is tightly coupled to the optical system used. Hence, there is a need to characterize the spectral response of cantilevers while simultaneously characterizing the optical setup used for the same.

Our aim in this study is to measure the wavelength-dependence of the IR thermomechanical response of several microcantilevers and to understand the observed response using a theoretical, physics-based model. Specifically, the model seeks to predict the spectral response (signal) and noise as a function of cantilever structure to allow design of sensing systems by rational selection of cantilevers. Our approach is based on previous work that predicted microcantilever thermomechanical sensitivity and noise [3, 12–14] but expands it to include spectral characteristics of the cantilevers and optical system. Though some groups have custom designed and fabricated bimaterial microcantilevers for IR measurements [15–17], most published studies have used commercially available microcantilevers [5–8, 10]. Hence, the model is validated by comparing predictions to experiments for six different types of commercially available microcantilevers. The results of the present article are directly relevant in both understanding IR measurements with both commercially available microcantilevers as well as for future optimization of instruments using microcantilevers.

MODELING CANTILEVER SENSITIVITY AND NOISE

The thermomechanical bending sensitivity of a microcantilever can be calculated from incident IR radiation, IR response characteristics of the cantilever, and the mechanical properties of the cantilever. For a beam consisting of two materials with different thermal expansion coefficients, the cantilever deflection can be expressed as [3, 18]

$$\frac{d^2z}{dx^2} = \frac{6(\alpha_s - \alpha_c)}{t_s + t_c} \left( \frac{t_c}{t_s K} \right) [T(x) - T_0]$$  \hspace{1cm} (1)

where
\[ K = 4 + 6 \left(\frac{t_s}{t_c}\right) + 4 \left(\frac{t_s}{t_c}\right)^2 + \frac{E_s}{E_c} \left(\frac{t_s}{t_c}\right)^3 + \frac{E_c}{E_s} \left(\frac{t_c}{t_s}\right), \]

\(z(x)\) is the vertical deflection, \(T(x) - T_0\) is the temperature difference between the cantilever and the ambient temperature at a location \(x\) along its length, \(\alpha\) is the thermal expansion coefficient, \(t\) is the layer thickness with subscripts indicating the substrate (s) or the coating (c) material, and \(E\) is Young’s modulus. In order to obtain an analytical solution for Eq. (1), several simplifications are employed in the heat transfer analysis. First, the incident radiation is assumed to be uniformly distributed over the cantilever area. Second, the Biot number based on cantilever width is about \(10^{-4}\), and it is assumed that the temperature varies along the length of the cantilever but that the temperature is uniform across the width and thickness of the cantilever. Thus, a one-dimensional heat transfer analysis is appropriate. The cantilever is assumed to lose heat along its length and due to thermal conduction to the air, where the effective heat transfer coefficient is \(h = 1,000 \text{ W/m}^2\text{-K}\) [19–21]. Radiative heat loss from cantilever is small compared to conduction and convection, because the cantilever temperature rise over room temperature is small.

With these assumptions and appropriate boundary conditions, the temperature distribution \(T(x)\) can be analytically described. Substituting \(T(x)\) into Eq. (1) yields the following analytical solution of the cantilever deflection:

\[
z(L) = 3(\alpha_s - \alpha_c) \left(\frac{t_s + t_c}{t_c^2 K}\right) \frac{P_\lambda}{(t_s + t_c + w)hL\beta^2} \times \left(\frac{\sinh(\beta L) - \beta L - \cosh(\beta L) + \frac{1}{2} \beta^2 L^2 + 1}{\beta}\right),
\]

where

\[
\beta = \sqrt{\frac{2(t_s + t_c + w)h}{(\gamma_s t_s + \gamma_c t_c)w}}, \tag{2}
\]

\(L\) is cantilever length, \(w\) is cantilever width, \(\gamma\) is the thermal conductivity of the cantilever, and \(P_\lambda\) is the spectral radiant power absorbed by the cantilever. The thermomechanical sensitivity of the cantilever, defined as angular displacement per unit spectral radiant power absorbed at the free end, is

\[
S = \left. \frac{1}{P_\lambda} \frac{dz}{dx} \right|_{x=L} = 3 \left(\alpha_s - \alpha_c\right) \left(\frac{t_s + t_c}{t_c^2 K}\right) \frac{1}{(t_s + t_c + w)hL} \left(\frac{L - \tanh(\beta L)}{\beta}\right). \tag{3}
\]

Though the above analysis provides a measure of sensitivity, cantilever noise must also be considered. In general, cantilever noise includes contributions from intrinsic factors such as thermomechanical noise and temperature fluctuations and extrinsic factors such as environmental vibration and instrument noise [22]. Here, we consider only thermomechanical noise because it has been reported to be two orders of magnitude larger than the noise due to temperature fluctuations for low quality factor \((Q \sim 100)\) microcantilevers.
Thermomechanical noise can be predicted from a continuous energy transformation between stored mechanical energy in the cantilever and thermal energy of the environment [12]. This energy conversion induces the thermal vibration of the cantilever, whose amplitude can be predicted using the equipartition theorem [23]. When the measurement bandwidth \( B \) is selected and the quality factor of the microcantilever \( Q \) is measured, the root mean square (rms) displacement of the cantilever tip \( \delta z_{th} \) due to thermomechanical noise is predicted to be [12]

\[
\sqrt{\langle \delta z_{th}^2 \rangle} = \sqrt{\frac{4k_BT B}{Qk\omega_0}}.
\]

where \( k_B \) is Boltzmann’s constant, \( T \) is absolute temperature, \( k \) is cantilever spring constant, and \( \omega_0 \) is mechanical resonance frequency of the microcantilever. This relation is established for a rectangular cantilever.

We evaluated the deflection sensitivity and signal-to-noise ratio (SNR) of 73 bimaterial microcantilevers available from the following vendors: MikroMasch (San Jose, CA, USA), NanoAndMore (Lady’s Island, SC, USA), Nanosensors (Neuchatel, Switzerland), and Veeco Probes (Camarillo, CA, USA). In order to search those appropriate for thermomechanical deflection measurements, cantilevers possessing a nominal spring constant outside the range of \( 0.01 < k < 1 \) N/m were not included [10]. For very stiff cantilevers, the cantilever will not bend much upon heating. For very soft cantilevers, thermomechanical noise will cause the cantilever to be unstable and unsuitable for bending measurements. For cantilevers having an appropriate nominal stiffness, the thermomechanical deflection sensitivity is predicted using Eq. (3) and the analytical SNR was obtained from the ratio of the theoretical deflection predicted by Eq. (2) to the theoretical noise predicted by Eq. (4). Based on this initial screening, we selected six cantilevers having different combinations of deflection sensitivity and SNR.

Table 1 lists each of the selected cantilever’s name, manufacturer, material composition and dimensions. Figure 1 shows the cantilever shapes and critical dimensions. All of the cantilever types in this study are V-shaped, except for Type B, which is rectangular.

<table>
<thead>
<tr>
<th>Cantilever</th>
<th>Type</th>
<th>Substrate material</th>
<th>( t_s ) (( \mu )m)</th>
<th>Coating material</th>
<th>( t_c ) (nm)</th>
<th>( L ) (( \mu )m)</th>
<th>( L_1 ) (( \mu )m)</th>
<th>( w ) (( \mu )m)</th>
<th>( 2d ) (( \mu )m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Long OTR4-35</td>
<td>SiN 0.50 Au</td>
<td>60</td>
<td>199.0</td>
<td>125</td>
<td>30.0</td>
<td>56.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>CSC17/ALBS</td>
<td>Si 2.00 Al</td>
<td>30</td>
<td>461.3</td>
<td>—</td>
<td>43.0</td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Long OTR8-10</td>
<td>SiN 0.70 Au</td>
<td>60</td>
<td>199.0</td>
<td>125</td>
<td>30.0</td>
<td>56.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Short OTR4-35</td>
<td>SiN 0.50 Au</td>
<td>60</td>
<td>100.0</td>
<td>75</td>
<td>15.5</td>
<td>25.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Short OTR8-10</td>
<td>SiN 0.70 Au</td>
<td>60</td>
<td>100.0</td>
<td>75</td>
<td>15.5</td>
<td>25.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Long CSC11/ALBS</td>
<td>Si 1.30 Al</td>
<td>30</td>
<td>197.6</td>
<td>140</td>
<td>40.6</td>
<td>49.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 1 Optical microscope pictures of rectangular and V-shaped cantilevers used in this study, showing key geometric parameters.

Table 2 Microcantilever response and ranking for an incident wavelength of 7.5 µm

<table>
<thead>
<tr>
<th>Cantilever</th>
<th>Meas.</th>
<th>Pred.</th>
<th>Measured noise (pm/√Hz)</th>
<th>Predicted noise (pm/√Hz)</th>
<th>SNR</th>
<th>Meas.</th>
<th>Pred.</th>
<th>Deflection ranking</th>
<th>SNR ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>127</td>
<td>127</td>
<td>1.28</td>
<td>1.748</td>
<td>99.2</td>
<td>72.7</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>B</td>
<td>114</td>
<td>111</td>
<td>0.634</td>
<td>0.718</td>
<td>180</td>
<td>155</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>49.3</td>
<td>52.9</td>
<td>0.448</td>
<td>0.445</td>
<td>110</td>
<td>119</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>D</td>
<td>17.8</td>
<td>23.3</td>
<td>0.398</td>
<td>0.454</td>
<td>44.7</td>
<td>51.3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>E</td>
<td>11.9</td>
<td>9.95</td>
<td>0.206</td>
<td>0.0810</td>
<td>57.8</td>
<td>122</td>
<td>5</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>F</td>
<td>9.32</td>
<td>9.79</td>
<td>0.385</td>
<td>0.120</td>
<td>24.2</td>
<td>81.6</td>
<td>6</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

A V-shaped cantilever can be approximated to be an equivalent rectangular cantilever of length \( L_1 \) and width \( 2\bar{d} \) from the parallel beam approximation, which allows the use of Eqs. (2) through (4) [24]. Table 2 compares the predicted and measured deflection and SNR of the six microcantilevers for an incident wavelength of 7.5 µm.

**EXPERIMENTAL SETUP AND EXPERIMENTS**

Figure 2 shows the experimental setup for cantilever characterization. A sintered silicon carbide rod (Newport [Irvine, CA, USA], 6363) is mounted in a monochromator illuminator (Newport [Irvine, CA, USA], 7340) and set to 1100 K in order to emit broadband light with the wavelength of maximum blackbody radiation at 2.63 µm. A spherical mirror coated with AlMgF\(_2\) (reflectivity 97.4% over this wavelength range) integrated with the monochromator illuminator focuses the light into the entrance slit of the monochromator. The monochromator is an Oriel 260 ¼ m (Newport, Irvine, CA, USA) equipped with a single grating of blaze wavelength optimized for 7 µm and a line density of 75 lines/mm. The monochromator emits a spectrally narrowband beam with a bandwidth of 100 nm in the 5–10 µm range. Before light enters the monochromator, an optical chopper (Stanford Research Systems [Sunnyvale, CA, USA], SR540) modulates the beam at \( f_0 = 380 \) Hz. The
Figure 2 Diagram of the experimental setup, where monochromatic infrared beam is incident upon a microcantilever mounted in a commercial atomic force microscope.

The IR light incident upon the bimaterial cantilever induces a cantilever temperature rise at the modulated frequency and in turn induces thermomechanical deflection at the same frequency. The frequency of the modulated light has been set to be much smaller than the inverse of the thermal time constant and also to be much smaller than the mechanical resonance frequency, such that the cantilever deflection corresponds to the incident IR radiation alone. The amplitude of the cantilever deflection is measured by an optical quad-cell readout system of an Agilent PicoPlus (Santa Clara, CA, USA) atomic force
microscope (AFM) system. The AFM optical readout output voltage is processed with a spectrum analyzer with an integration bandwidth of 1 Hz and integration time of 20.48 s.

In order to quantify the IR radiation incident upon the cantilever, the spectral efficiency of the monochromator ($\eta_{\lambda M}$) was measured using a Bruker Vertex (Billerica, MA, USA) 70 Fourier transform infrared (FT-IR) spectrometer. Spectra were acquired over the mid-IR range at an undersampling ratio of 2 referenced to the He-Ne laser to provide a free scanning spectral range of 7,200–0 cm$^{-1}$. Interferograms were acquired at a nominal resolution of 4 cm$^{-1}$, signal averaged using 32 scans and fast Fourier–transformed using triangular apodization. The radiant power at each monochromator wavelength ($\dot{Q}_{\lambda MO}$) was obtained from the spectrum, which was then divided by the predicted monochromator input radiant power to calculate the $\eta_{\lambda M}$ as

$$
\eta_{\lambda M} = \frac{\dot{Q}_{\lambda MO}}{\varepsilon_{\lambda E} I_{bE} A_E F_{EM} \eta_m},
$$

where $\varepsilon_{\lambda E}$ is the emissivity of the IR emitter, $I_{bE}$ is the spectral blackbody intensity of the IR emitter, $A_E$ is the surface area of the IR emitter, $F_{EM}$ is the view factor from the light source to the mirror within the IR emitter [25], and $\eta_m$ is the mirror reflectance.

Figure 3 shows the measured monochromator spectral efficiency $\eta_{\lambda M}$ as a function of wavelength. Generally, $\eta_{\lambda M}$ increases with wavelength in a given spectral range in spite of the fact that the blaze wavelength of the grating is 7 µm. Above the blaze wavelength, the second- and third-order effect of the grating becomes notable, because the grating efficiency starts to increase significantly from the half the blaze wavelength (3.5 µm) according to the manufacturer’s data sheet. This multiple-order radiations of the grating enlarge the magnitude of $\dot{Q}_{\lambda MO}$ and, in turn, result in high $\eta_{\lambda M}$ above the blaze wavelength.

Separately, the cantilever IR characteristics were measured using a Perkin-Elmer (Waltham, MA, USA) Spotlight 400 FT-IR imaging system, which consists of a rapid-scan spectrometer coupled to a microscope equipped with a linear array detector. Transmittance and reflectance examinations of bimaterial cantilevers were recorded over the 7,200–0 cm$^{-1}$ range and a range of 3,000–704 cm$^{-1}$ (or 3.33–14.2 µm) was saved for analysis. Spectral transmittance was obtained from the ratio of the transmission intensity of the cantilever by the reference intensity of air. Similarly, reflectance was measured from the ratio

![Figure 3](image-url) Transmission efficiency of the monochromator measured using FT-IR.
of the reflection intensity of cantilever surface to the reference intensity of a gold-coated glass slide. Then, the radiative energy balance for a transmitting layer was adopted to calculate absorbance at each wavelength, which states that the sum of transmittance, reflectance, and absorptance is unity [26].

Figure 4 shows the cantilever-measured spectral absorbance over the mid-IR range. The strong wavelength dependence of the cantilever absorbance suggests that the thermomechanical response will depend upon the wavelength of incident light. For each optical property and each cantilever, the IR measurement was repeated 32 times and averaged to minimize the uncertainties in measurements. Because the cantilever width is in the range of 25–50 µm and the beam spot size of the spectrometer is 15 × 15 µm², diffraction may affect the measurements but is not expected to play a significant role in measuring the spectral properties at the center of the cantilever because the spot size is smaller than the cantilever feature being measured. Considering the reasonable match of theory and experiment (vide infra), we do not believe that diffraction has a significant bearing on the results. Further measurement uncertainty may also arise from a tilt in the microcantilever when it is placed on the sample stage of the IR microscope. As shown in Figure 4 and reported by Wig and coauthors [26], the absorption is dependent on the material composition and thicknesses of the layers of bimaterial microcantilevers. In Figure 4, a higher thickness ratio of the two beam materials ($t_c/t_s$) correlates with higher absorbance. The Au-SiNx cantilevers were observed to absorb nearly 50% more than the Al-Si ones in this spectral region. As expected, material composition and thickness ratio between the substrate and the metal layers affect the IR absorption and present an opportunity to adjust for optimization of these cantilevers. Multiple small peaks in the spectra are likely due to both the interference effect between the surfaces of the cantilever and scattering from the surface. Recently, detailed optical models for IR microscopy have been proposed that allow for rigorous modeling and predictions of scattering [27, 28]. To possibly improve the model proposed here, rigorous optical theory must be extended to the measurements and the results compared.
the model proposed here must be considered to be a starting point in modeling cantilever response in the IR. Certainly, for image formation applications using cantilevers, the model proposed here must be merged with the optical models proposed in Davis et al. [27, 28].

With the above measurements, the system parameters are all known and it is possible to predict the IR incident upon the cantilever, the cantilever absorption, and the corresponding cantilever temperature distribution and thermomechanical deflection. Equation (2) was used to calculate spectral radiant power absorbed by the cantilever. The spectral radiant power absorbed by the cantilever is approximated to be the cumulative result of spectral blackbody intensity of the IR emitter, emissivity of the IR emitter, monochromator transmission efficiency, and absorption characteristics of microcantilevers, which can be expressed as

\[ P_\lambda = \dot{Q}_\lambda \alpha_\lambda A_c / A_s, \]

where \( \alpha_\lambda \) is the spectral absorptance of the bimaterial cantilever, \( A_c \) is the surface area of the cantilever, and \( A_s \) is the beam focal spot area.

RESULTS AND DISCUSSION

The cantilever deflection was monitored by an AFM optical readout system and was proportionally translated into AFM output voltage. For the calibration of the cantilever detector deflection voltage to deflection distance, the deflection sensitivity of each cantilever was measured and multiplied by the AFM output voltage. Figure 5 shows measured cantilever deflection as a function of illuminating IR wavelength.

The agreement between measurement and prediction is reasonable for the simple model that we have proposed, demonstrating that the model and our overall approach capture the important physics behind cantilever response. The overall amplitude of the thermomechanical deflection predicted by Eq. (2) agrees well with measurement, as does the spectral profile. No fitting parameters or normalization was required to obtain the good agreement between measurement and prediction. Hence, Eq. (2) is useful for predicting photothermal sensitivities of the bimaterial cantilevers in the selected spectral region. However, spectra in Figure 5 exhibit discrepancies in the spectral regions at 5–6.5 and...
The differences between these curves likely arise from atmospheric absorption from water vapor (H$_2$O) and carbon dioxide (CO$_2$). Specifically, the fundamental vibrational modes of H$_2$O at 6.3 µm and CO$_2$ at 9.4 µm contribute to absorption that is apparent in single-beam spectra [29]. In turn, the attenuation of the radiative energy into the cantilever possibly leads to a smaller thermomechanical deflection than the predicted deflection within these regions [30]. Though effort may be expended in precisely correcting for such effects, we note that the application of cantilevers for sensing or IR spectroscopy will involve absorbance calculations. Hence, there is limited value in actually correcting for atmospheric effects. The effect on agreement with theory is minimal and within the error seen in other parts of the spectrum. Hence, we have presented the spectra as would be typically recorded for a single-beam measurement in a typical analytical instrument.

Figure 6 shows the fluence predicted and measured for one Type A cantilever. The predicted fluence is calculated from the model of light flow through the system that accounts for spectral reflectivity of the mirrors, spectral reflectivity of the mirrors, spectral absorptance of the cantilever, and the measured size of the spot. Separately, Eq. (2) allows the fluence to be calculated from the measured cantilever thermomechanical bending. As in Figure 5, the predictions and measurements compare well.

Table 2 shows measured and predicted SNR values for an incident wavelength of 7.5 µm. The AFM optical readout voltage is affected by noise sources as described previously. The contribution of these noises was captured by performing a Fourier transform on the AFM output signal at the modulation frequency in the absence of IR incidence on the microcantilever. The data were recorded at the same integration bandwidth (1 Hz) and an integration time of 5 min. The magnitude of the noise was measured to be in the order of $10^{-6}$ to $10^{-5}$ V, forming a baseline for the AFM output signal, which then corresponds to the thermomechanical deflection measurement baseline noise of 0.206–1.28 pm. We had previously hypothesized that thermomechanical noise was dominant for these measurements. Hence, thermomechanical noise of the cantilever at off-resonance frequency was predicted by Eq. (4) and compared with the measured SNR. The predicted SNR is
of the same order of magnitude as measured SNR except for type E and F cantilevers. These cantilevers also have the smallest thermomechanical deflections, suggesting that the proportional thermomechanical noise becomes lower and other sources become significant. Interestingly, cantilevers that undergo relatively larger thermomechanical deflections exhibit relatively higher SNR. We can surmise that the noise likely saturates at a certain level or grows much slower than the signal and is not simply proportional to the signal (deflection). The practical implication of this observation is that cantilever deflection alone does not predict SNR. Hence, in addition to materials type and relative thickness of the two layers, absolute deflection of the cantilever is likely to be another important parameter in designing optimal cantilevers for sensing.

CONCLUSION

We have developed a theoretical model to predict thermomechanical sensitivity and noise for bimaterial microcantilevers over a mid-IR region. The developed model was tested using six commercially available cantilevers over the wavelength range 5–10 µm, which is important for chemical analyses. An analytical model was established and the spectral absorptance of the cantilevers was measured using IR spectroscopy. The predictions of microcantilever thermomechanical bending sensitivity showed good agreement with measurements over 6.5–9 µm wavelength bandwidth. We also demonstrated that thermomechanical noise was dominant in measurements and matched experimentally measured values. Together, the analytical model and measurements reported in this manuscript indicate the key design parameters for using biomaterial microcantilevers for spectral sensing in IR spectral region.

REFERENCES


