Optomechanical spectroscopy with broadband interferometric and quantum cascade laser sources

L. Tetard,1 A. Passian,1,2* R. H. Farahi,1 B. H. Davison,1 and T. Thundat1

1Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6123 USA
2Department of Physics, University of Tennessee, Knoxville, Tennessee 37996, USA
*Corresponding author: passianan@ornl.gov

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The spectral tunability of semiconductor–metal multilayer structures can provide a channel for the conversion of light into useful mechanical actuation. Responses of suspended silicon, silicon nitride, chromium, gold, and aluminum microstructures are shown to be utilized as a detector for visible and IR spectroscopy. Both dispersive and interferometric approaches are investigated to delineate the potential use of the structures in spatially resolved spectroscopy and spectrally resolved microscopy. The thermoplasmonic, spectral absorption, interference effects, and the associated energy deposition that contributes to the mechanical response are discussed to describe the potential of optomechanical detection in future integrated spectrometers. © 2011 Optical Society of America

OCIS codes:

Manipulations of materials at the structural levels or via bandgap engineering provide a means to achieve many fascinating phenomena, ranging from filtering exhibited by stratified materials [1] to negative refraction exhibited by metamaterials [2–4]. Applications are equally intriguing and diverse, such as plasmonic enhancement [5], cloaking [6,7], and invisibility [8]. Recently, optomechanics has also emerged as a means to manipulate mesoscopic systems [9,10] by taking advantage of electromagnetic–mechanical couplings involving photothermal, radiation pressure [11], and stochastic forces [12]. Notable among these is the formation of an optical interferogram (e.g., in a Michelson interferometer), with important applications in spectral measurements of the molecular signatures of materials and spatial measurements of subnanometer displacements. These capabilities have been at the core of developing the Fourier transform IR (FTIR) spectrometer, gravitational wave detector [13], and laser Doppler vibrometers [14]. As a result, the optical interaction with microstructures continues to attract study, such as analyzing the transport of photogenerated carriers [15] or the observation of Fano-like resonances [16]. The optical response of the typical atomic force microscope (AFM) silicon (Si) or silicon nitride (Si3N4) probes, the microcantilevers [17], in conjunction with the introduction of various nanophotonic and waveguide structures [18], indicate their potential application as nanomechanical spectrometers. Furthermore, due to the ease of interfacing microstructures with noble metal thin films and nanostructures, thermoplasmonic and other plasmonic processes [19] can be capitalized upon as new actuation mechanisms. In this Letter, by investigating (1) an optomechanical interferogram and (2) the photothermal response of micro-mechanical structures to mid-IR lasers, we introduce the concept of Fourier transform optomechanical spectroscopy (FTOS).

The experimental arrangement is shown in Fig. 1. A broadband source (1.5–25 μm) and a tunable pulsed quantum cascade laser (QCL) [20] (9.25–9.81 μm) provide radiation that can interact with a series of metal-coated AFM cantilevers. The core components of a typical (1) interferometric measurement intended to demonstrate FTOS with oscillator C1, (2) dispersive measurement on C2, and (3) deflection measurement on C3 are shown in Fig. 1. Noting that measurement (3) is used to read out the deformation of a probe, it is clear that such arrays of oscillators may be integrated for specific applications in optomechanics [21]. Data were obtained by angle controlled illumination and optical deflection detection using a dimensional and a multimode AFM system. Focusing a collimated 1 in. (2.54 cm) diameter broadband beam (Spectrum GX, Perkin Elmer), we characterized the resonators in the range of 1.5–25 μm and compared the
results with theory in Fig. 2. The data were collected by averaging at a 4 cm$^{-1}$ resolution. Spectra from Au–Si$_3$N$_4$ and Al–Si probes are shown in Figs. 2(a)–2(c) and Figs. 2(d)–2(f), respectively, and Fig. 3. To further analyze the data acquired from the studied probes $C_i$, we simulated the optical response of their material do-

![Image](optics-letters-vol-36-no-17-september-1-2011-fig-2.png)

Fig. 2. (Color online) Optomechanics of (a)–(c) Au–Si$_3$N$_4$ and (d)–(f) Al–Si AFM probes. Spectra for incidence at the semiconductor layers in (a), (b), (d), and (e), and the insets of (c), (f), with the data in the mid-IR in (a) and (d), and the theoretical $s$ and $p$ polarization (incidence $30^\circ$) absorption in (b) and (e). Insets (a) and (d) show the 1.5–25 μm spectra, while the case of $0^\circ$ is shown in inset (e). The inset in (b) shows the properties of Si$_3$N$_4$ [22]. In (c) and (f), the responses in the visible and near-IR are presented when the metal layer is exposed, while the insets show the semiconductor exposure. Arrows indicate the He–Ne line used in the oscillation detection of the probe.

![Image](optics-letters-vol-36-no-17-september-1-2011-fig-3.png)

Fig. 3. (Color online) (a) Amplitude and (b) phase of the QCL beam profile measured with an Al–Si microcantilever ($k = 0.03$ N/m). Probe’s response to (c) $f_p$ and (d) $W_p$ of the QCL output obtained by lock-in measurement. The two data sets and their numerical fits in (c) show the noise excited resonances of the probe. $O$, in (d), is the operational point used in (c) with $f_p = 100$ kHz.
electromagnetic energy in the material layers. This Poynting energy forms the source term for the heat equation that can be solved for the specific boundary conditions of the structure to yield the transient temperature distribution \( T(x, t) \). Consequently \( T(x, t) \) leads to a deformation \( d(x, t) \) as a result of the asymmetric thermal expansion (each material layer possessing a different thermal expansion coefficient). Thus, for a fixed velocity \( v \) of the moving mirror in Fig. 1 yielding an optical path difference (OPD) of \( \delta = 2vt \), the signal from the PSD can be expressed as a function of time \( t \) as \( S(t) = \int_0^\infty S(\nu) \cos(4\pi vt)d\nu \), where \( S(\nu) \) is proportional to the responsivity of the probe and the amplifier as a function of wavenumber \( \nu \). Since \( S(t) \propto d(x, t) \) (within an electronic amplification factor and calibration), we can solve for the transient probe response and obtain \( d(x, t) = \sum_{k=1} g_k(t) |\omega_k|^2 \), where \( g_k(t) \) is the \( k \)-th eigenmode of the probe (eigenfrequency \( \omega_k \)) and

\[
g_k(t) = \int_0^1 \Phi_k(u)du \int_0^\infty w(u, \tau) e^{-\eta(t-\tau)} \sin \omega_k(t-\tau) d\tau,
\]

while \( w(u, \tau) \) represents the bulk force [12] and \( \eta \) is related to the damping. Note that, with a proper apodization applied to \( S(t) \) when processed for the FFT, the spectral resolution of FTOS is related to both the maximum OPD of the scan and the response time of the probe. Since the modulation frequency of the interferogram is proportional to \( \nu \) and \( v \), we obtain, for \( \nu = 1 \text{ cm}^{-1} \) and \( 4000 \text{ cm}^{-1} \), a frequency of 8 kHz, which is well within the response time of all the probes used (compared with the lowest lying resonances of 10.2 and 22 kHz for the Si–Al and Si–N–Cr–Au probes). Comparing the interferograms obtained using the FTOS with those generated by the standard KBr detector of the FTIR, we established that FTOS readily resolves the fastest variation in amplitude.

We conclude that optomechanical systems can provide spectrally resolved detection of radiation and thus be integral parts of microspectrometers. Advances in metrology and sensing demand an understanding of the optomechanical properties of novel actuators, particularly for high resolution imaging and detection. The optical response must be catered accordingly, depending upon whether the structure is to be used in a direct chemical/biological sensing application, that is, responding to the transfer of the thermal absorption energy from the sample in contact with the structure, or in the measurement of the scattered light from the sample, that is, a direct photothermal scheme. The presented spectra show that both the interferometric and single beam parameters can trigger various couplings between the elastic, the optical, and the thermo-optic responses. While any thermoelastic dissipation and potential Fano-like structures are implicit in our dynamic (QCL) measurements of the Q-factor and the form of the resonance lines, they appear of little or no consequence in the interferometric measurements, strengthening the potential of FTOS for high resolution spectroscopy. We introduced the concept of thermoplasmonic actuation via the nonradiative decay of surface plasmons that can provide a significant channel for energy deposition.

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References
Queries

1. Please provide two to six OCIS codes from http://www.opticsinfobase.org/submit/ocis/
2. SI equivalents are typically given for English measurements. Is 2.54 cm okay for 1 in.?
3. Please check the references to Figs. 2(f) and 2(e) in the last two sentences of this paragraph. Are these correct?