Absolute deflection measurements in a MEMS/NEMS Fabry-Perot interferometry system

Roberto DeAlba[1,2], Christopher B. Wallin[1,2], Slava Krylov[3], and B. Robert Ilic[1]

[1] National Institute of Standards and Technology, Center for Nanoscale Science and Technology, Gaithersburg, MD 20899
[2] Maryland Nanocenter, University of Maryland, College Park, MD 20742
[3] School of Mechanical Engineering, Tel Aviv University, 69978 Ramat Aviv, Israel
robert.ilic@nist.gov

Micro- and nano-electromechanical systems (MEMS/NEMS) are among the most sensitive devices for detection of ultra-weak forces, masses, and displacements. The small scale of these structures affords them very high frequencies (MHz-GHz), high quality factors, rich nonlinear phenomena, low thermal occupancies, and many other beneficial traits that make them ideal as sensors and testbeds for new physics, including quantum motion. Moreover, their electrical integrability and compatibility with CMOS fabrication make them extremely promising as electro-mechanical circuit elements, non-volatile memory cells, and energy harvesters.

Perhaps one of the most robust methods for laboratory detection of MEMS/NEMS motion is Fabry-Perot laser interferometry, which measures relative motion between the vibrating structure and the stationary substrate underlying it. This method is non-invasive, does not require electrical integration of the device under test, does not require an external reference mirror (which is susceptible to environmental vibrations), and does not suffer from the strong background or feedthrough signal of capacitive detection. This common setup has long been used to study Si cantilevers, Si_3N_4 membranes, suspended graphene membranes, MoS_2 membranes, metal nanowires and carbon nanotubes, among many other systems. Because the setup utilizes interferometry, the wavelength of light can be used as a metric by which to calibrate device motion. However, because the device-substrate distance is typically fixed, this calibration can be difficult to achieve. Indeed, for most measurements, the vibration amplitude is maintained small relative to the laser wavelength (1 nm to 10 nm compared to ≈ 600 nm) so that the detection system remains linear, and the experimenter is left with only a measurement proportional to the vibration amplitude with the proportionality constant unknown.

In this work, we use MEMS cantilevers of varying dimensions to characterize the interferometry detection method (Figure 1) in the large-amplitude regime – i.e. oscillations spanning more than half a wavelength of light. Because of strong readout nonlinearities in this regime, sinusoidal device motion results in extremely non-trivial measurements in the time domain – encoding information about the cantilever vibration amplitude, backplane distance, and cantilever angle. We have developed analytical models to fit the experimental data and extract these physical parameters, and use this technique to map out multiple vibrational modes and analyze Duffing behavior (Figures 2, 3). Furthermore, we extend this analysis to measurements made in the frequency domain by a multi-frequency lock-in amplifier to enable absolute deflection measurements with both high accuracy and high throughput (Figure 3c). Our aim is to develop a robust model covering a wide range of device geometries (including ultra-fine devices such as nanowires), to demonstrate the utility of large-amplitude oscillations as a calibration metric for measurements in the low-amplitude regime, and to possibly enable measurement of device material properties through accurate knowledge of vibration amplitude and static deflection.

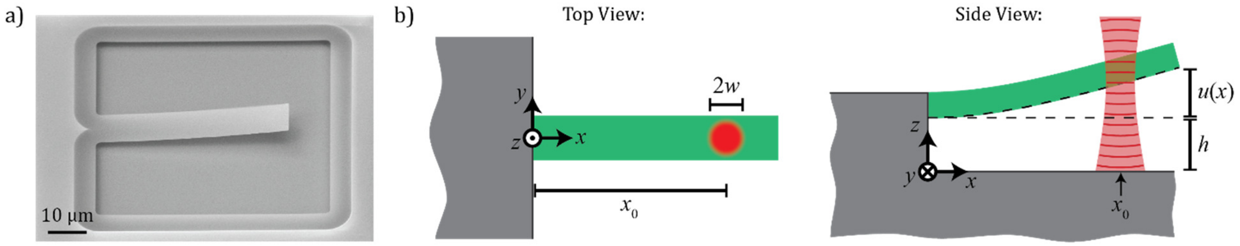

Figure 1. a) Scanning electron micrograph of a Si_3N_4 cantilever used to characterize our optical interferometry system. The device dimensions are (length × width × thickness) 50 µm × 10 µm × 100 nm. b) Schematic of the detection system. An incident laser (wavelength $\lambda = 640$ nm) is focused on the MEMS cantilever with a spot size of ≈ 1 µm, and reflected laser light is collected by a high-speed photodetector (not shown). Device motion relative to the backplane encodes information about the vibration amplitude, static displacement, and cantilever angle in the reflected laser power that can be measured at sufficiently large deflections ($u > \lambda/2$).

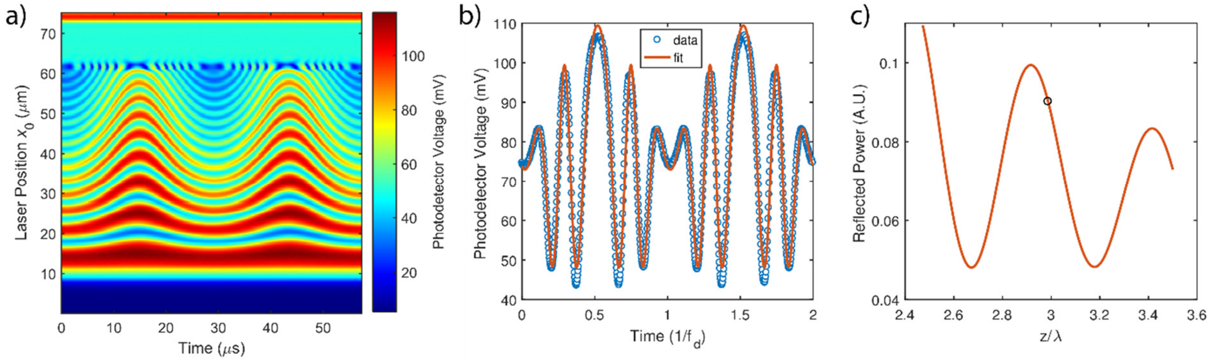

Figure 2. a) The fundamental mode of a 50 µm cantilever, as imaged by the nonlinear optical interferometer. The image was taken by stepping the detection laser along the length of the device (x_0 in Figure 1) and recording the power collected by our photodetector. Each horizontal row of pixels corresponds to an individual time-trace measured via an oscilloscope. b) A row of data from (a) taken at $x_0 = 34$ µm. c) The underlying interference pattern at $x_0 = 34$ µm extracted from the fit in (b). Sinusoidal device motion centered at the open circle with an amplitude of ≈ 0.51×λ produces the fit shown in (b).

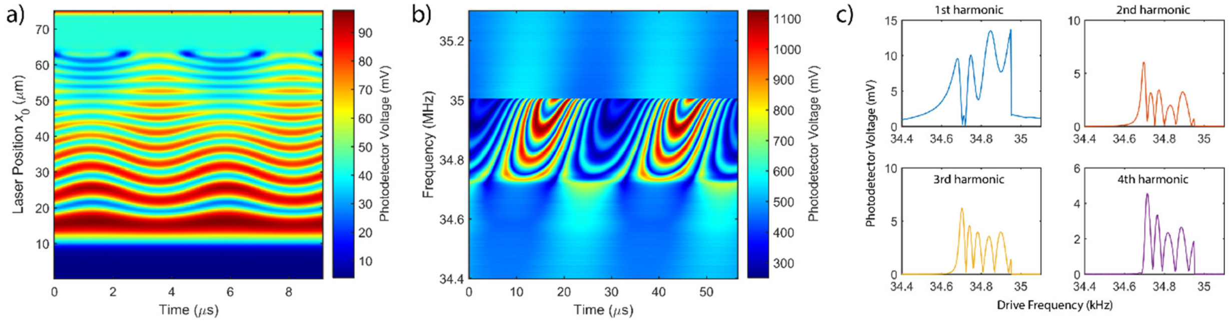

Figure 3. a) Mode 2 of a 50 µm cantilever, measured in a similar manner to Figure 2. b) A frequency sweep of the same device, showing an overdriven Duffing response with strong optical nonlinearity. Note that the vertical axis here is the drive frequency f_d. c) A Duffing resonance peak as measured by a multi-frequency lock-in amplifier. The harmonics correspond to signal measured at frequencies $f_d, 2f_d, 3f_d$, and $4f_d$.