Absolute deflection measurements in a MEMS/NEMS interferometry system

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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 to GHz), high quality factors, rich nonlinear phenomena, and many other beneficial traits that make them ideal as sensors and testbeds of fundamental physics. Fabry-Perot laser interferometry is a widespread and robust technique for probing MEMS/NEMS devices because it is non-invasive and provides exceptional motion sensitivity ($\approx$ 1 pm $\mathrm{Hz}^{-1/2}$) from DC to roughly 100 MHz. This technique utilizes the silicon substrate beneath the MEMS/NEMS device as a static reference mirror, as shown in Figure 1(a). This type of interferometry system is compatible with a wide range of MEMS/NEMS materials, from common insulators and conductors to graphene and other atomically-thin membranes.

Despite the many strengths of this experimental technique, it suffers from two main drawbacks. Firstly, the measured signal becomes highly nonlinear for device displacements larger than $\lambda/4$, where λ is the laser wavelength. Secondly, because the silicon backplane is immovable, there is no simple or established technique for calibrating device motion. As such, published results utilizing this setup typically report deflection in “arbitrary units.” In this work, we focus on fully characterizing the nonlinear aspects of a MEMS/NEMS Fabry-Perot interferometer and developing a generalized approach to calibrate device motion based the laser wavelength. We demonstrate how to quickly and accurately measure the interference pattern of a MEMS system, as shown in Figure 1(b), simply by exciting large-amplitude motion and measuring the reflected laser power in the time domain. This procedure provides detailed information about the resonator’s vibration amplitude and static deflection, as shown in Figure 2. We further demonstrate how a single calibration can be applied to subsequent measurements taken at lower amplitudes and to measurements taken in the frequency domain (e.g. by a lock-in amplifier). We validate our results by comparing static deflection measurements of a sample cantilever to measurements taken with a commercial optical profilometer.

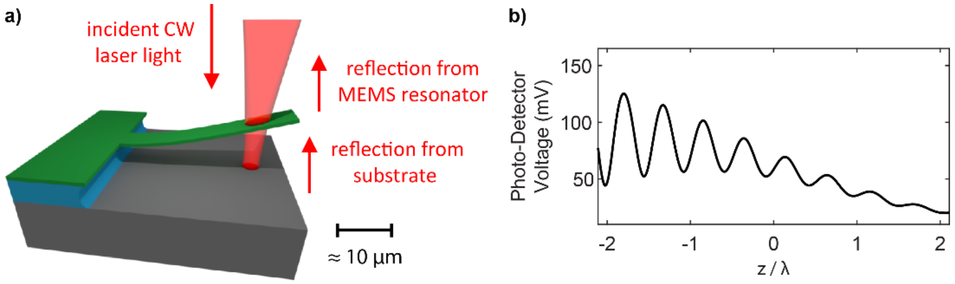

Figure 1: The MEMS/NEMS Interferometry System. a) A continuous wave (CW) laser is focused onto the MEMS/NEMS resonator. Light reflected by the resonator interferes with light reflected by the silicon substrate. The total reflected laser power is measured by a photo-detector (not shown). b) A sample interference pattern measured using a silicon nitride cantilever. Here, z = 0 corresponds to the cantilever's equilibrium position, and positive z corresponds to motion away from the silicon substrate.

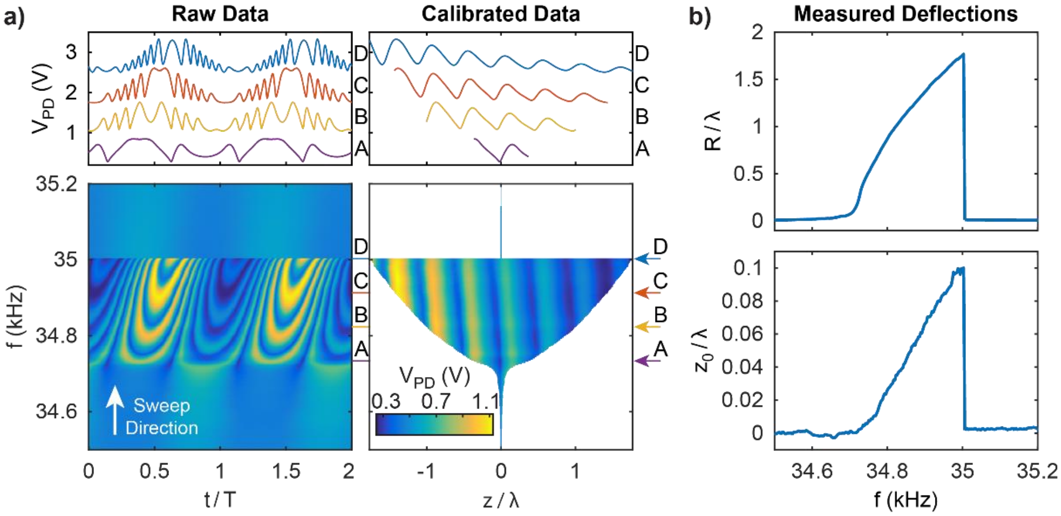

Figure 2: Calibrating a Duffing resonance. a) A frequency sweep of a silicon nitride cantilever measured using the optical interferometry system. Data was recorded with the laser ($\lambda \approx 640$ nm) focused near the cantilever free end. Successive oscilloscope traces were measured while the cantilever was inertially driven with the drive frequency, f, incrementally swept from $f \approx 34.5$ kHz to $f \approx 35.2$ kHz. Left panels: the raw data as collected by an oscilloscope. Units of time, t, have been normalized by the drive period, $T = f^{-1}$. Right panels: the same data after calibration, plotted versus displacement, z. In lower panels, the pixel color corresponds to the measured photo-detector voltage (V_{PD}). Upper panels display individual oscilloscope traces (vertically offset for clarity) and correspond to horizontal slices of the lower panels at the f values indicated by A-D. Note that the calibrated data reveals the shape of the interference pattern of this system; straight, nearly vertical interference fringes are clearly visible. b) The cantilever deflections extracted from the calibrated data in (a). Shown are the vibration amplitude, R, and the static deflection, z_0. Both plots indicate a nonlinear spring constant, with R resembling a Duffing resonance.