Limit Cycle Oscillations in Silicon Structures Using Opto-Thermal Excitation

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Primary CNF Tools Used: Heidelberg mask writer - DWL2000, Hamatech hot piranha, DISCO dicing saw, GCA 6300 DSW 5x g-line wafer stepper, Unaxis 770 deep silicon etcher, Anatech plasma asher, Leica CPD300 critical point dryer, Zygo optical profilometer, Zeiss Supra SEM

Abstract:

Self-sustaining micro-oscillators may find applications in fields such as time-keeping and sensing, due to their high quality factors and frequency stability. This work involves the study of pairs of opto-thermally driven oscillators and their characteristics such as synchronization to each other and frequency entrainment to an external drive. The experimentally observed phenomena are complemented by theoretical and numerical studies.

Summary of Research:

Our work involves the study of the nonlinear characteristics of limit cycle oscillators (LCO's) and the emergence of synchronization in such systems. A limit cycle oscillator consists of a resonating element supplied by a constant energy source with a built-in positive feedback between the LCO's motion and the external energy source. Such active oscillations can be distinguished from a resonance response caused by an external periodic force applied to a passive resonating element [1].

We focus on single and pairs of clamped-clamped beam micro-resonators which were fabricated on a 0.75″ × 0.5″ silicon-on-insulator (SOI) chip with a 205 nm silicon device layer. The steps of general photolithography were followed with the exposure done on a GCA 5x g-line stepper.

After development, the silicon device layer was etched using the Bosch process. The devices were released using a buffered oxide etch (BOE) of the 400 nm silicon dioxide layer underneath followed by critical point drying. An image of the released devices taken using scanning electron microscopy (SEM) is shown Figure 1.

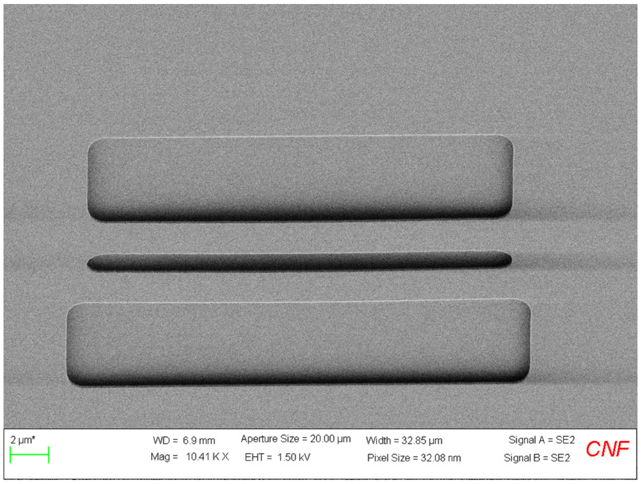

Figure 1: SEM image of clamped-clamped silicon beams fabricated from an SOI stack with 205 nm silicon device layer and 400 nm silicon dioxide.

The SOI chip with the micro-resonators is indium-bonded to a piezoelectric shaker housed in a vacuum chamber at a pressure of approximately 1e-7mBar. A continuous-wave laser beam with wavelength 633 nm is focused at the center of the microresonators, and part of the light is absorbed by the resonator, while part is transmitted and reflected back to it, thus setting up a Fabry-Perot interference cavity. The absorbed light causes the beam to undergo thermal expansion, which in turn modulates the amount of light absorbed. Thus, the microresonator undergoes self-sustaining limit cycle oscillation. The reflected laser beam modulated due to the oscillations is directed to a high-speed photodetector and its frequency content is recorded using a spectrum analyzer. The analyzer also serves a second purpose of providing the input signal to the piezoelectric shaker when an external inertial drive is required [2].

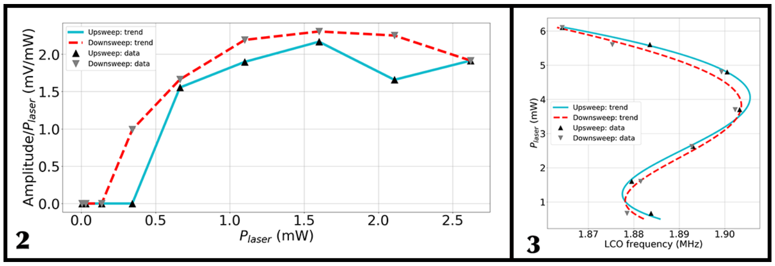

Figure 2, left: The birth of LCO in a Hopf bifurcation: variation of normalized signal amplitude with laser power upsweep and downsweep. Figure 3, right: Variation of the LCO frequency with laser power upsweep and downsweep.

From the resonance response it can be noted that the resonator exhibits spring softening, i.e. the frequency decreases with increasing amplitude of motion. The external drive amplitude is kept fixed and the frequency is swept up and down. The plateaus in the drive LCO curves correspond to entrainment regions. Hysteresis can again be noted in this experiment. It is expected that the frequency span for entrainment will become larger for higher drive amplitudes.

The appearance of a limit cycle response is shown in Figure 2. The laser is focused on a silicon beam 36 μm long and 2 μm wide and the laser power hitting the sample is swept up and then down. In the laser upsweep, we see that the LCO appears at around 0.3 mW of incident power and the signal amplitude normalized by the laser power is approximately constant. The transition to limit cycle is accompanied by a Hopf bifurcation [3], which is seen in numerical models for this system. The downsweep curve shows hysteretic behavior of the oscillator with laser power. For the same device, the frequency response of the LCO with laser power is shown in Figure 3. The response is non-monotonic with laser power. It is also noted that at low laser power the LCO's have greater frequency stability than at higher powers.

Frequency entrainment refers to the phenomenon of an external periodic driving force causing the frequency of the LCO to match that of the drive. The key parameters that determine entrainment of an LCO is the frequency detuning between the LCO and the external drive and the drive amplitude. Figure 4 shows the results of an entrainment experiment on a single LCO. The external drive is provided by the piezoelectric shaker and the swept frequency and amplitude are controlled by the spectrum analyzer [4]. The undriven LCO response and the resonance responses are plotted as a reference for the entrainment curves.

Conclusions and Future Steps:

Opto-thermally driven limit cycle oscillations are observed in the clamped-clamped silicon microresonators. They show other nonlinear behavior such as frequency entrainment to an external inertial drive. Further experiments will be conducted on pairs of beams coupled elastically via silicon bridges. Coupling between two frequency-detuned oscillators is expected to result in self-synchronization of the beams. Further parameter spaces such as coupling strength, frequency detuning between two LCO's, and the influence of the external drive will be explored.

References:

[1] Pikovsky, Arkady, et al. "Synchronization: a universal concept in nonlinear sciences." No. 12. Cambridge university press, 2003.

[2] Blocher, David. "Optically driven limit cycle oscillations in MEMS." (2012).

[3] Aubin, Keith, et al. "Limit cycle oscillations in CW laser-driven NEMS." Journal of microelectromechanical systems 13.6 (2004): 1018-1026.

[4] Blocher, David B., Alan T. Zehnder, and Richard H. Rand. "Entrainment of micromechanical limit cycle oscillators in the presence of frequency instability." Journal of Microelectromechanical Systems 22.4 (2013): 835-845.

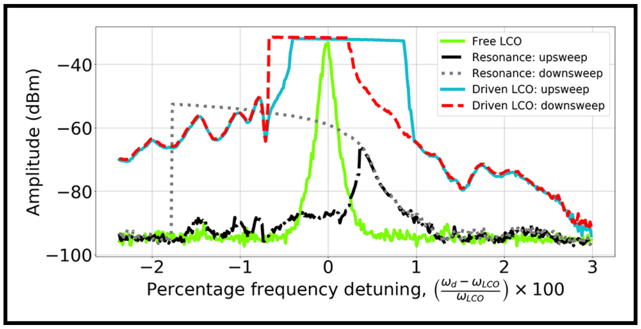

Figure 4: Frequency entrainment of an LCO by an external inertial drive on frequency upsweep and downsweep. The regions of entrainment correspond to the plateaus in the peak tracking signals. The free LCO response and resonance response on frequency upsweep and downsweep are also plotted for reference.