Synchronization and Bistability in Coupled Opto-Thermal MEMS Limit Cycle Oscillators

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Abstract:

In this work, we study the nonlinear dynamics of pairs of mechanically coupled, opto-thermally driven, MEMS limit cycle oscillators. We vary three key parameters in the system — frequency detuning, coupling strength, and laser power, to map the device response. The coupled oscillators exhibit states such as the self-synchronized state, quasi-periodic state, drift state, and bistability. Specifically, we show that the laser power can be used to change the effective frequency detuning between the oscillators and at high laser powers the system shows irregular oscillations due to the existence of bistable states and sensitive dependence on system parameters.

Summary of Research:

Coupled oscillators at the microscale exhibit strong nonlinearities owing to the large deformations relative to the device dimensions [1]. This makes them suitable as experimental testbeds to study nonlinear dynamics. We study clamped-clamped beams that are nominally 40 µm long, 3 µm wide and 205 nm thick. Frequency detuning is introduced in the system by varying the lengths of adjacent oscillators and coupling is affected by short bridges between the devices as well as elastic overhangs near the anchor points. The bridges are spaced apart by 3 µm and are simultaneously excited into limit cycle oscillations using a single continuous wave laser beam at a wavelength of 633 nm. The resonator structure forms a Fabry-Perot interferometer where the absorbance and reflectance are modulated with the cavity gap. The interference setup allows for the driving and detection of oscillations [2]. A top-view of a sample device with the edges outlined and the laser beam aligned is shown in Figure 1.

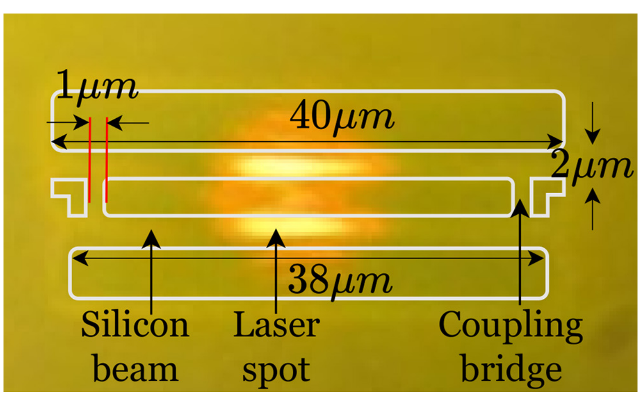

Figure 1: Optical microscope image of a sample device with the beams outlined and key dimensions labelled. The silicon device layer thickness is 205 nm. The laser spot aimed at the center of the device is used to drive and detect oscillations.

For plotting the synchronization region, the laser power was kept constant at approximately 1.3 mW striking the devices. The spectral responses were recorded for 25 different devices. These consisted of pairs of oscillators at five different coupling and five detuning levels. In all 25 devices, the reference oscillator was of length 38 microns. The other oscillators in the pair were of length {42, 40, 38, 36, 34} microns corresponding to a minimally coupled frequency detuning percentage of {−18%, −10%, 0%, +10%, +14%} respectively. A heat map of the difference in frequencies between the two oscillators for the 25 different devices is shown in the 5 × 5 grid in Figure 2. The plot shows a region of synchronization with boundaries marked in white. The spectra corresponding to three different dynamical states are also shown.

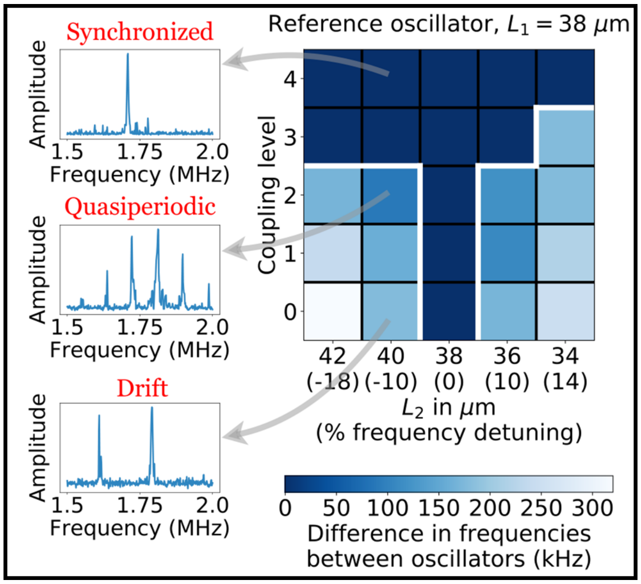

Figure 2: Experimental results showing the difference in limit cycle frequencies between pairs of oscillators in the frequency detuning vs. coupling strength space forming an Arnold tongue region of synchronization. The spectra of the system show drift, quasi-periodic, and synchronization states.

At low coupling, the oscillators are drifting with two prominent peaks in the spectrum. At moderate coupling strengths, the system shows quasi-periodic behavior with multiple sidebands in the spectrum in addition to two prominent peaks. This is the result of amplitude modulation of the oscillators due to the coupling.

At higher coupling strengths, inside the Arnold tongue region, the oscillators synchronize and the spectra collapses to a single prominent peak corresponding to the frequency of locking.

We also studied the device response at a fixed frequency detuning of −10% and by varying the coupling strength and laser power [3]. The resulting map in shown in Figure 3.

At minimal coupling, the devices exhibit a drift response for all laser powers. We note that the limit cycle frequencies decrease with an increase in laser power due to the strong amplitude softening behavior of the post-buckled beams, but the frequency detuning between the oscillators increases with an increase in laser power. This implies that the frequency detuning between the oscillators can be varied using the continuously varying laser power parameter.

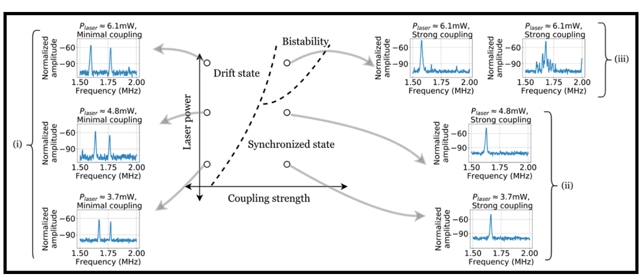

Figure 3: A map of the experimentally recorded dynamics of a pair of coupled MEMS oscillators (i) drift state at minimal coupling strengths, (ii) synchronized state in the presence of strong coupling at low laser powers, and (iii) co-existence of two stable states, i.e. synchronized oscillations and quasi-periodic oscillations in the presence of strong coupling at high laser powers.

At strong coupling, the oscillators show synchronized oscillations at low and moderate laser powers. At high laser powers, the system shows irregular oscillations with the system switching between two stable states: the synchronized state and the quasiperiodic state rapidly, due to the presence of noise in the system such as an unstable laser source. The system switching between the two states and exhibiting a broadband spectrum in the intermediate time is shown in Figure 4.

Conclusions and Future Steps:

In this work, we charted the behavior of pairs of coupled opto- thermally driven oscillators in the coupling, detuning, and laser power parameter space. The rich dynamics exhibited by such devices furthers our understanding of nonlinear oscillations and may have utility in devices such as sensors, filters, oscillator-based computers, and time-keeping devices.

References:

[1] S. Tiwari and R. N. Candler, "Using flexural MEMS to study and exploit nonlinearities: A review," Journal of Micromechanics and Microengineering, vol. 29, no. 8, Aug. 2019, Art. no. 083002.

[2] Blocher, David. "Optically driven limit cycle oscillations in MEMS." Cornell Thesis, https://hdl.handle.net/1813/31202 (2012).

[3] A. Bhaskar, M. Walth, R. H. Rand, and A. T. Zehnder, "Bistability in coupled opto-thermal micro-oscillators," Journal of Microelectromechanical Systems, (to appear) 2022.

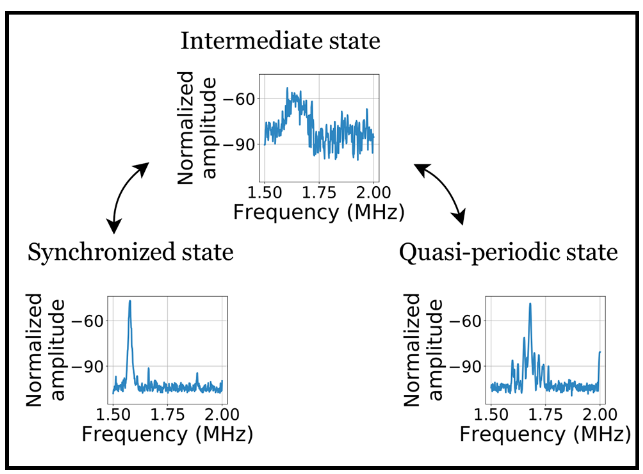

Figure 4: Bistability manifests as a broad-band spectral response in strongly coupled oscillators in the experiments (center). The oscillators rapidly switch between the synchronized state (left) with a single prominent peak in the spectrum, and the quasi-periodic state (right) with multiple satellite peaks, due to sensitive dependence of the system on the dynamical variables.