Nonlinear dynamics of 2D materials

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Summary. Two-dimensional (2D) materials such as graphene are model systems for investigating nonlinear dynamics at the nanoscale. They exhibit phenomena such as intermodal coupling and stochastic switching already at amplitudes that are only a few nanometers with potential applications that are yet to be harnessed. In this talk, I will give an overview of the recent advancements in nonlinear dynamic studies of 2D materials with particular focus on methods for utilizing nonlinearity in ultra-thin mechanical systems.

Introduction

Nanomechanical systems are ubiquitous in a variety of applications in modern technology. The advent of 2D materials, and the ability to fabricate one-atom thick membranes, have made it possible to reach the ultimate sensing capabilities that not so long ago were only dreamed of. But this revolutionary downscaling has been associated with constraints on the linear dynamic range of these mechanical systems since signatures of nonlinearity already emerge at amplitudes that are only a few nanometers [1].
Although the field of nonlinear dynamics dates back several centuries, its implications in atomically thin membranes have remained largely unexplored. In this talk, we present methods and experiments for understanding and utilizing nonlinear dynamic phenomena in 2D material membranes. Our aim is to shed light on the intricate modal couplings and the strong interplay between noise and nonlinearity and discuss the means to harness these effects.

Results

Our experiments are performed on multilayer graphene nanodrums with a diameter of 5 µm, which are transferred over a cavity etched in a layer of SiO_2 with a depth of 285 nm. We use a blue laser to opto-mechanically modulate the tension of the membrane, and a red laser to detect the motion, using interferometry. To control the static deflection of the drum, in some of our experiments we also place a local electrode at the bottom of the cavity. The presence of this electrode will allow us to controllably deflect the membrane downwards and use that as an electromechanical knob to tune the tension and thus resonance frequencies of the drum. Moreover, to reduce the damping from the surrounding air we perform the experiments in a vacuum chamber. A schematic of the setup is shown in Fig. 1a together with microscopic image of the graphene drum in Fig. 1b.

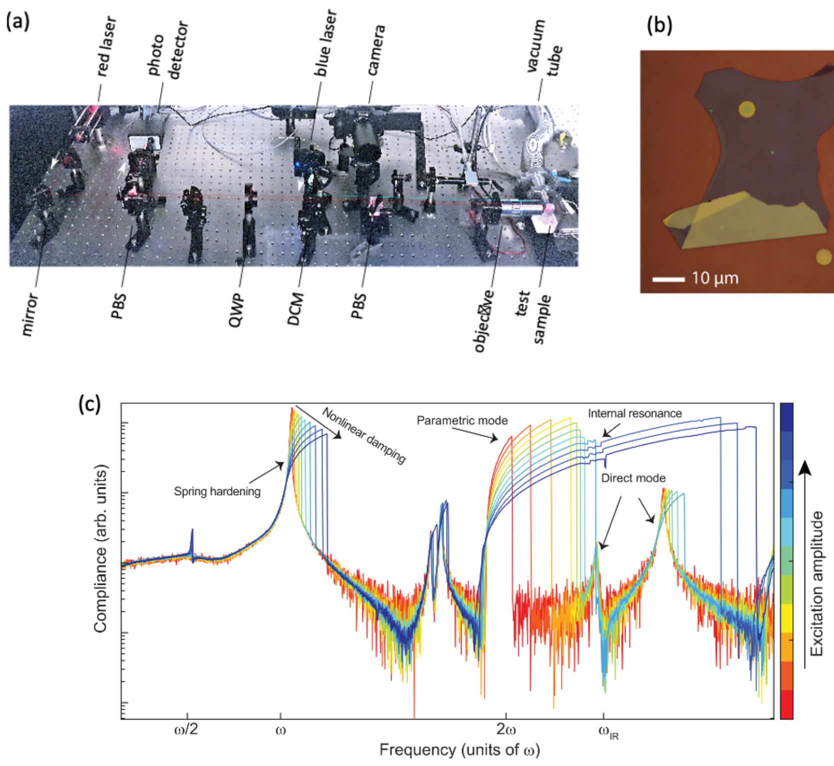

Figure 1: (a)The opto-mechanical set-up for actuating and detecting the motion of the graphene membranes; (b) Microscopic image of the graphene drum [2]; (c) Measurement of the nonlinear dynamic response as a function of the excitation amplitude [3].

By increasing the power of the blue laser, we detect a plethora of nonlinear dynamic phenomena over a wide frequency range. This includes the presence of spring hardening nonlinearity already at forces that are only a few pN, the emergence of nonlinear damping, parametric resonance, parametric -direct internal resonance [2] and a range of direct-direct 2:1 internal resonance. We show that it is possible to make use of these nonlinear effects. For instance, by adding random fluctuations to the drive level, it is possible to obtain stochastic switching rates of 4 kHz between the stable states of the graphene Duffing resonator that are 100 times faster than current state-of-the-art, at effective temperatures 3000 times lower (See Figure 2a and 2b), providing the possibility to transduce weak signals through stochastic resonance. Moreover, by tuning the tension of the membrane using a back gate, we can control internal resonance conditions, obtain quasiperiodic oscillations and thus generate mechanical frequency combs (see Figure 2c).

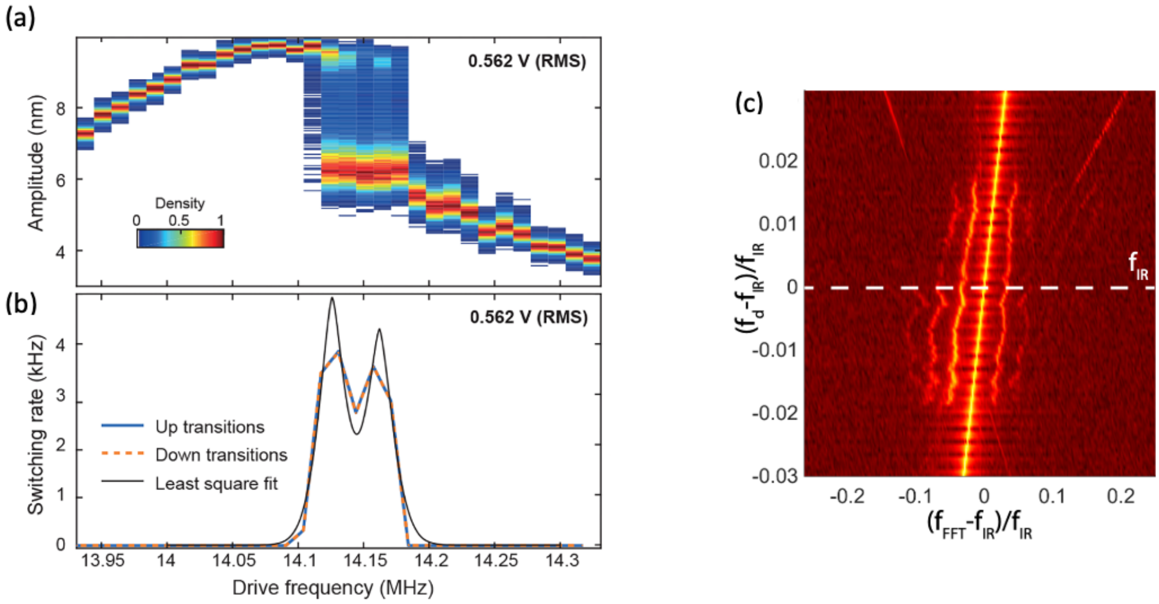

Figure 2: (a) stochastic switching in a graphene resonator close to room temperature [4]; (b) Up and down switching rates as a function of fixed drive frequency [4]; (c) Emergence of frequency combs at internal resonance.

Conclusions

In conclusion we showed that 2D material resonators exhibit a wealth of nonlinear dynamic phenomena and discussed the means to detect them. We showed that these atomically thin membranes provide a platform for investigating a range of modal interactions and the strong interplay between fluctuations and nonlinearities, thus paving the way towards new opportunities for utilizing nonlinear dynamics at smallest length scales and very fast (MHz frequency) time scales.

References

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