NON-LINEAR DYNAMICS IN OPTO-MECHANICAL OSCILLATORS

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ABSTRACT
Cavity opto-mechanics enabled opto-mechanical oscillators leverage coupling between high quality factor mechanical and optical resonances in a micro-resonator. The inherently high quality factors make such systems susceptible to various non-linearities. This paper presents the first reported experimental demonstration of various non-linear dynamics observed in a silicon opto-mechanical oscillator, and specifies operating conditions required to inhibit these effects. We present four non-linear effects viz. i) oscillations of parasitic mechanical modes, ii) chaotic mechanical oscillations, iii) multi-GHz oscillations driven by two photon absorption, and iv) coherence of the excited mechanical oscillations, similar to optical frequency combs.

KEYWORDS
Opto-mechanical oscillator, non-linearity, chaotic oscillations, opto-mechanical oscillator coherence

INTRODUCTION
Opto-mechanical oscillators (OMOs) leverage the force exerted by laser light circulating in an optical resonant cavity to excite mechanical oscillations. Light can excite oscillations in mechanical resonators in several ways [1] – radiation pressure (RP) driven [2-4], via the optical gradient force [5] or through electrostriction [6] and other nonlinear opto-mechanical interactions [7]. These oscillators are attractive due to the absence of electrical feedback, resulting in zero flicker noise [3] and being all-optically transduced in nature, they enable designing MEMS oscillators with dielectric materials with such as SiO_2 and Si_3N_4. These materials have higher frequency-quality factor (f-Q) products than silicon, which results in lower oscillation linewidth, and hence lower phase noise [3,8].

The threshold laser power required to launch self sustained mechanical oscillations depends strongly on the optical and mechanical quality factors (Q). Previous studies have shown [8] that higher Qs are necessary for low threshold power, and hence better power added efficiency of these oscillators. However, these high Q systems are susceptible to non-linearities that could severely limit their performance. The following section provides details on the design of the silicon opto-mechanical resonator used to study these effects. The subsequent section highlights some of these phenomena that are focused on in this paper, along with experimental observation of these effects.

DESIGN AND CHARACTERIZATION OF THE SILICON OMO
A coupled silicon opto-mechanical resonator is fabricated following the process flow detailed in previous work [9]. The ring geometry (radius = 21µm, ring annulus = 3.8µm) is chosen such that the fundamental radial expansion (breathing) mode of the structure has a resonant frequency corresponding to 70MHz. Fig. 1 shows an SEM of this structure.

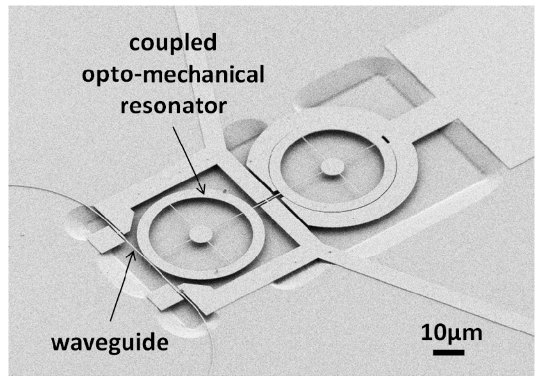

Figure 1: Scanning electron micrograph (SEM) of the fabricated silicon opto-mechanical resonator, comprising of two coupled micro-ring resonators. Laser light is coupled into optical resonances of the resonator via the waveguide.

An optical transmission spectrum obtained for this device by sweeping the wavelength of the laser light coupled into the waveguide reveals multiple high Q optical resonances, as shown in Fig. 2. To operate the device as an oscillator, the laser is coupled to an optical resonance and the laser power is set above the oscillation threshold for exciting the breathing mode via radiation pressure [8].

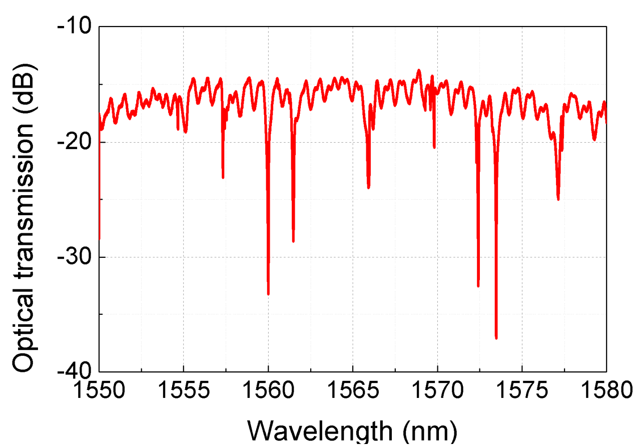

Figure 2: Optical transmission spectrum of the silicon opto-mechanical resonator. Laser light is coupled into the waveguide at the input grating coupler and light collected from the output grating coupler is measured on an optical power meter. The input laser wavelength is swept to obtain the spectrum.

Fig. 3 shows the setup used for the experimental demonstrations highlighted in the following section.

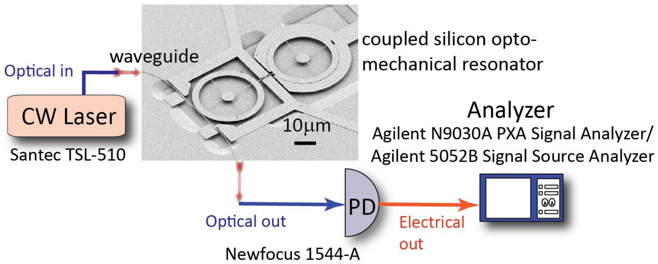

Figure 3: Illustration of the experimental setup. The continuous wave laser is used to excite oscillations, which are sensed using the photo-detector and measured on a signal analyzer. Phase noise measurements are conducted using a signal source analyzer.

NON-LINEARITIES IN OMOs

Oscillations of parasitic mechanical modes

Since the resonator itself constitutes the frequency selection element in the OMO, the opto-mechanical interaction could potentially also launch self-oscillations of any parasitic mechanical modes of the resonator, provided the laser power is larger than the threshold for the corresponding mode.

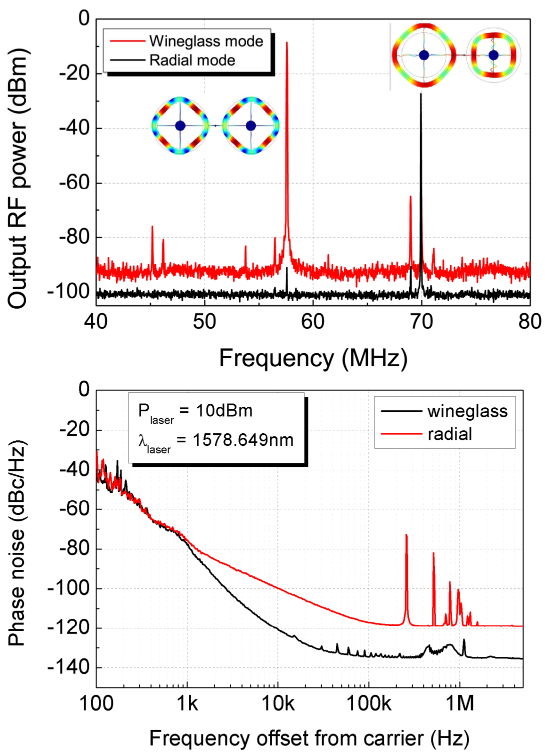

Figure 4: (top) RF spectrum at output of photo-detector. The RP induced oscillations can be switched from radial mode (black curve) to wineglass mode (red curve) by choosing appropriate laser detuning. P_{laser} = 15dBm. Insets: FEM mode shapes using COMSOL. (bottom) Comparison of phase noise of both modes.

The radiation pressure coupling is controlled by the detuning [2], which can thus be used to select the desired mechanical mode by matching the detuning to the mechanical resonance frequency. Fig. 4 shows excitation of the wineglass mode (58MHz) instead of the radial mode if the detuning is not set correctly.

When multiple opto-mechanical interactions are in play, it is also important to inhibit competing oscillation phenomena; for e.g. gradient force driven oscillations [5] of the waveguide on account of the large electric field gradient between the light field inside the waveguide and the cavity. To avoid these effects, it is necessary to suppress the mechanical Q of undesirable modes, or tailor the frequency selection by controlling the laser detuning. Fig. 5 shows RF spectrum for oscillations of the n=3 bending mode of the waveguide excited by gradient force. Higher harmonics are generated on account of non-linear modulation [9].

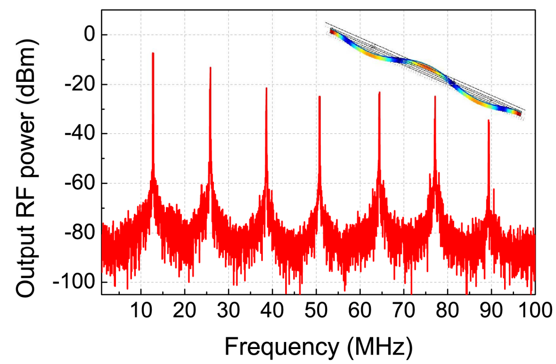

Figure 5: Gradient force induced oscillations of the n=3 in plane mode of the waveguide at 12MHz.The laser detuning is chosen such that the radiation pressure effect is not dominant. Inset: FEM simulated mode shape of waveguide using COMSOL Multiphysics.

Chaotic oscillations

At higher input laser powers, by tuning the laser further into resonance, the oscillations can enter chaotic regime as previously shown by T. Carmon et al. [10]. The chaotic behavior evolves from the continuous laser input, in absence of any external modulation, perturbation or feedback, showing that the chaotic vibration is an intrinsic cavity property. Similar observations have also been noticed for membrane resonators [11]. Fig. 6 shows chaotic oscillations of the OMO in one such operating regime.

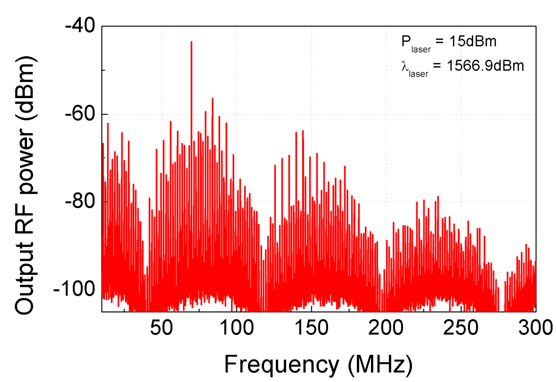

Figure 6: RF spectrum of chaotic oscillations of the silicon opto-mechanical oscillator.

Two-photon absorption driven oscillations in silicon

Higher input laser power can also cause other undesirable effects such as self-pulsing driven by two photon absorption (TPA) in silicon, as previously shown by S. Malaguti et al. [5]. The resulting multi-GHz oscillations are converted into RF signal by the photo-detector employed in an OMO system. Self-pulsing and chaotic oscillations are non-linearities inherent to the optical and mechanical cavities respectively in the OMO, and hence it is desirable to use low laser power to avoid these effects. Fig. 7 shows harmonics of oscillations observed at 4.22GHz on account of TPA.

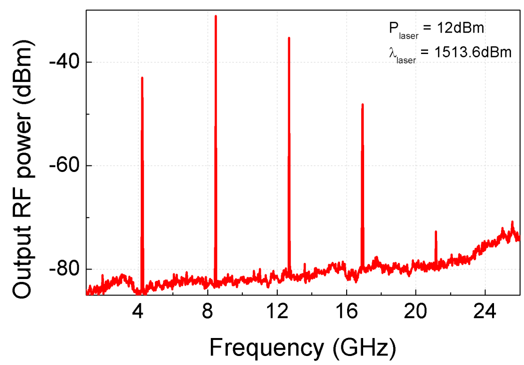

Figure 7: Oscillations on account of self-pulsing are observed at 4.22GHz when the laser power is increased for a high Q optical mode (Q>50,000).

Coherence of mechanical oscillations

Finally we highlight experimental observation of phase noise reduction and "coherence" of oscillations in the 70MHz oscillator, as the laser is tuned further into the optical resonance. The oscillator dynamics are strikingly similar to the non-linear dynamics observed in the generation of optical frequency combs reported by J. Li et al. [13], as shown in Fig. 8. The physical origin of this observation in OMOs is currently under investigation.

CONCLUSION AND FUTURE WORK

In conclusion, we highlight the rich diversity of nonlinear effects inherent to OMOs. Both radiation pressure and gradient force driven oscillation mechanisms compete in the silicon opto-mechanical resonator system presented here, and choosing the appropriate detuning and laser power ensures selection of the desired mechanical mode. Chaotic oscillations and multi-GHz oscillations driven by TPA in these silicon resonators can also be curbed by maintaining low laser powers. The coherent behavior similar to optical frequency combs warrants further study and deeper understanding into the origins for the phase noise reduction. Table 1 summarizes these insights.

The authors acknowledge Prof. Tal Carmon and Dr. Jamil Abo-Shaeer for engaging discussions on the topics presented in this paper. The research was supported with funding from DARPA Optical Radiation Cooling and Heating in Integrated Devices (ORCHID) program. The devices used for these experiments were fabricated at the Cornell NanoScale Science & Technology Facility (CNF).

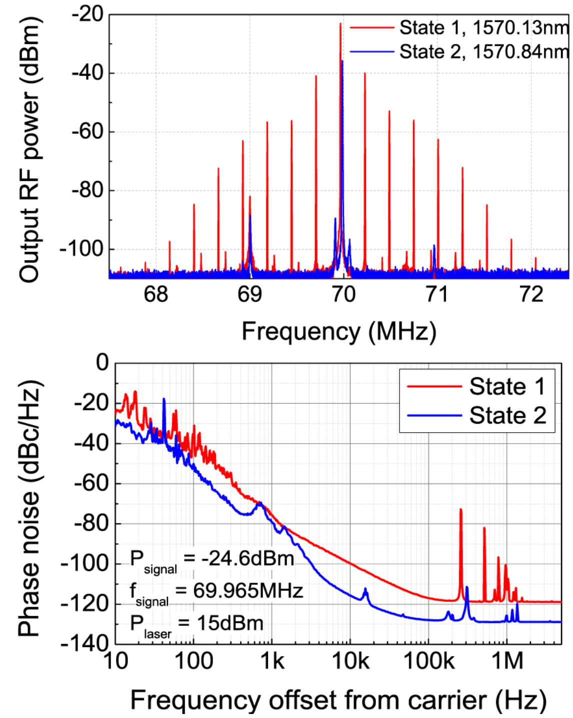

Figure 8: Experimental observation of "coherence" in OMOs. The phase noise of the 70MHz oscillator is reduced by 10dB by detuning the laser further into resonance. The RF spectrum (top panel) and phase noise (bottom panel) are strikingly similar to dynamics observed in optical frequency comb generation [13].

Table 1: Effects of non-linearities in silicon OMO and operating conditions to curb these effects.

Non-linearity	**Signature**	**Inhibiting condition**
Parasitic mechanical mode excitation	Oscillation of undesired mechanical mode	Reduce mechanical Q of undesired modes in design and set detuning equal to desired mechanical mode frequency for optimal coupling
Chaotic mechanical oscillations	Oscillation period doubling, and non-periodic continuum [10]	Operate with lower Q optical resonance whenever possible, and choose larger detuning and lower laser power
Two photon absorption	Self-pulsing leading to multi-GHz oscillations	Operate with lower laser power and lower optical Q
Coherence of mechanical oscillations	Phase noise reduction at lower detuning	Cause under investigation

REFERENCES

[1] A. Cho, “Putting Light's Light Touch to Work as Optics Meets Mechanics”, Science, vol. 328, no. 5980, pp. 812-813 (2010).
[2] T. J. Kippenberg and K. J. Vahala, “Cavity Opto-Mechanics”, Optics Express, vol. 15, no. 25, pp. 17172-17205 (2007).
[3] S. Tallur, S. Sridaran and S. A. Bhave, “A Silicon Nitride Optomechanical Oscillator with Zero Flicker Noise”, 25th IEEE International Conference on Micro Electro Mechanical Systems (MEMS 2012), Paris, France, pp. 19-22 (2012).
[4] T. Beyazoglu, T. O. Rocheleau, K. E. Grutter, A. J. Grine, M. C. Wu and C. T.-C. Nguyen, “A Multi-Material Q-Boosted Low Phase Noise Optomechanical Oscillator”, 27th IEEE International Conference on Micro Electro Mechanical Systems (MEMS 2014), pp.1193-1196 (2014).
[5] Q. Lin, J. Rosenberg, X. Jiang, K. J. Vahala, and O. Painter, “Mechanical Oscillation and Cooling Actuated by the Optical Gradient Force”, Physical Review Letters, vol. 103, 103601, (2009).
[6] M. Tomes and T. Carmon, “Photonic Micro-Electromechanical Systems Vibrating at X-Band (11-GHz) Rates," Physical Review Letters, vol. 102, 113601, (2009).
[7] A. A. Savchenkov, A. B. Matsko, V. S. Ilchenko, D. Seidel, and L. Maleki, “Surface Acoustic Wave Opto-Mechanical Oscillator and Frequency Comb Generator”, Optics Letters, vol. 36, no. 17, pp. 3338-3340, (2011).
[8] S. Tallur, S. Sridaran, S. A. Bhave and T. Carmon, “Phase Noise Modeling of Opto-Mechanical Oscillators”, IEEE Frequency Control Symposium (FCS 2010), pp. 268-272, (2010).
[9] S. Tallur and S. A. Bhave, “Partial Gap Transduced MEMS Opto-Acoustic Oscillator Beyond GHz”, IEEE Journal of Microelectromechanical Systems, vol. 24, no. 2, pp. 422-430, (2015).
[10] T. Carmon, M. C. Cross and K. J. Vahala, “Chaotic Quivering of Micron-Scaled On-Chip Resonators Excited by Centrifugal Optical Pressure”, Physical Review Letters, vol. 98, 167203 (2007).
[11] Y. Lu, M. Pandey, and A. Lal, “Chaotic Behaviour of a Membrane Resonator with Nanowire Array”, Solid State Sensor, Actuator and Microsystems Workshop (Hilton Head 2012), pp. 121-124, Hilton Head Island, South Carolina, June 3-7, 2012.
[12] S. Malaguti, G. Bellanca, A. de Rossi, S. Combrié and S. Trillo, “Self-Pulsing Driven by Two-Photon Absorption in Semiconductor Nanocavities”, Physical Review A, vol. 83, 051802, (2011).
[13] J. Li, H. Lee, T. Chen and K. J. Vahala, “Low-Pump-Power, Low-Phase-Noise, and Microwave to Millimeter-Wave Repetition Rate Operation in Microcombs”, Physical Review Letters, vol. 109, 233901 (2012).

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