PARAMETRIC AMPLIFICATION AND PHONONIC FREQUENCY COMB GENERATION IN MoS_2 NANOELECTROMECHANICAL RESONATORS

S M Enamul Hoque Yousuf[1*], Yunong Wang[1*], Jaesung Lee[1],
Steven W. Shaw[2,3], and Philip X.-L. Feng[1*]
[1]Department of Electrical & Computer Engineering, Herbert Wertheim College of Engineering,
University of Florida, Gainesville, FL 32611, USA
[2]Department of Mechanical & Civil Engineering,
Florida Institute of Technology, Melbourne, FL 32901, USA
[3]Department of Mechanical Engineering, and Department of Physics & Astronomy,
Michigan State University, East Lansing, MI 48423, USA

ABSTRACT

This paper reports on extraordinarily strong parametric amplification and spectral linewidth narrowing effects in atomically thin molybdenum disulfide (MoS_2) resonant nanoelectromechanical systems (NEMS), by applying the electrical pump signal at local gate. It also demonstrates phononic frequency comb (PnFC) formation based on 2:1 mode coupling during the degenerate parametric amplification. For a single-layer (1L) MoS_2 resonator, we measure the displacement spectral density without and with electrical parametric pumping and calculate the parametric gain and linewidth narrowing. We observe a parametric gain as high as ~10,000 (80dB) and spectral linewidth narrowing factor of ~5000 with 153mV pump voltage at $2f$. Since there is another mode present near $2f$, driving the device at $2f$ enables mode coupling between the fundamental mode and the mode near $2f$, and generates a PnFC with tunable comb spacing. The exceptional parametric amplification and spectral linewidth narrowing opens new possibilities towards building high performance atomically thin NEMS resonators for sensing applications.

KEYWORDS

Parametric amplification, parametric resonator, gain, phononic frequency comb (PnFC), two-dimensional (2D) materials, quality (Q) factor.

INTRODUCTION

Atomically thin NEMS resonators based on two-dimensional (2D) materials have demonstrated remarkable characteristics including broad dynamic range (DR) and ultrawide frequency tunability [1,2]. However, electrical readout of miniscule resonance motions of these devices is challenging because the intrinsic thermomechanical noise floor is overwhelmed by the noise from the electronics used at the front end of the measurement system. Quality (Q) factors of 2D resonators can be limited because of various extrinsic damping effects. To increase the signal amplitude and Q of 2D resonators, parametric amplification has been proposed to enhance the device motion at resonance frequency f with drive frequency of $f_p \approx nf$, where n is an integer ($n \geq 2$) [3-6]. Recent experiments on photothermal parametric pumping of undriven thermomechanical noise spectra have demonstrated giant parametric amplification with gains up to 71dB and spectral linewidth narrowing factor up to 1.8×10^5 [6]. Toward on-chip integration of parametric pumping, electrical parametric pumping is desired. Phononic frequency comb (PnFC), the phononic analogue of optical frequency comb in the radio frequency (RF) domain has been reported in microelectromechanical systems (MEMS) [7] and NEMS [8]. In NEMS resonators, strong mode coupling is required to coherently transfer energy between different modes via internal resonances and thus to generate PnFCs [8]. Atomically thin circular drumhead resonators using 2D semiconductor membranes, with wide frequency tuning to satisfy internal resonance conditions, provide an ideal platform for realizing PnFCs.

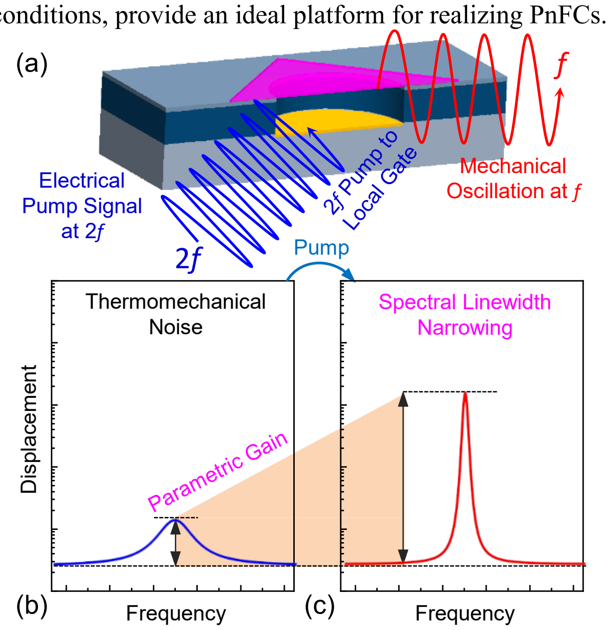

Figure 1: (a) Illustration of parametric amplification using time-domain signal in 2D NEMS resonator. Intrinsic thermomechanical noise spectral density, (b) before and (c) after electrical parametric pumping. The pump signal introduced at the local gate increases the signal amplitude with gain G along with spectral linewidth narrowing effect.

In this study, we realize highly efficient electrical parametric pumping via a local gate, and simultaneously measure the undriven thermomechanical noise spectra in a single-layer (1L) MoS_2 drumhead resonator. Undriven thermomechanical noise measurement enables exploring the full range of parametric amplification by directly amplifying the intrinsic noise floor. We experimentally demonstrate parametric gain up to ~10,000 before the device goes into parametric oscillation. The exceptional linewidth narrowing factor of ~5000 reveals the efficient electrical pumping in the sub-threshold regime (before saturation). We also observe a PnFC near the 1st mode by pumping near the 3rd mode to engender 2:1 mode coupling.

DEVICE DESIGN AND FABRICATION

The sapphire substrate for the electrostatically tunable MoS_2 2D NEMS resonators is fabricated by using various photolithography and etching steps compatible with standard NEMS fabrication process (Fig. 2). An exfoliated 1L MoS_2 is transferred onto this substrate using an all-dry transfer method, to make a drumhead resonator with 3μm diameter. A local gate configuration with the sapphire substrate provides electrostatic control of individual drumheads located on the same chip with significantly reduced parasitic effects. The single-layer nature of the MoS_2 is confirmed by Raman spectroscopy showing two prominent peaks at E^1_{2g}=385.44cm^{-1} and A_{1g}=403.65cm^{-1}, with a separation of 18.21cm^{-1} between them.

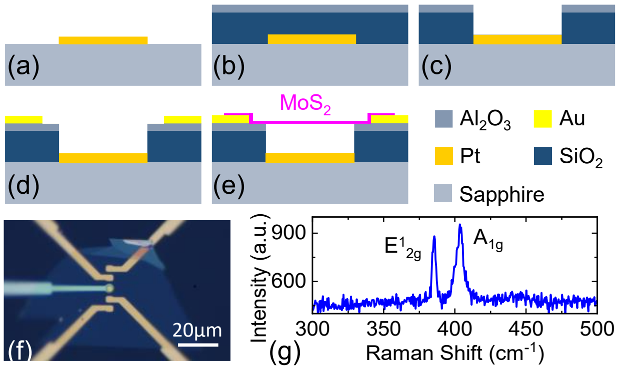

Figure 2: Fabrication process for the drumhead resonator. (a) Local gate patterning. (b) SiO_2 deposition and Al_2O_3 deposition. (c) RIE to form 290nm-deep trench. (d) Metal deposition for top electrodes. (e) All-dry transfer of the MoS_2 layer. (f) An optical image of the fabricated 1L MoS_2 drumhead resonator. (g) Raman signal showing E^1_{2g} and A_{1g} modes at 385.44cm^{-1} and 403.65cm^{-1}, respectively.

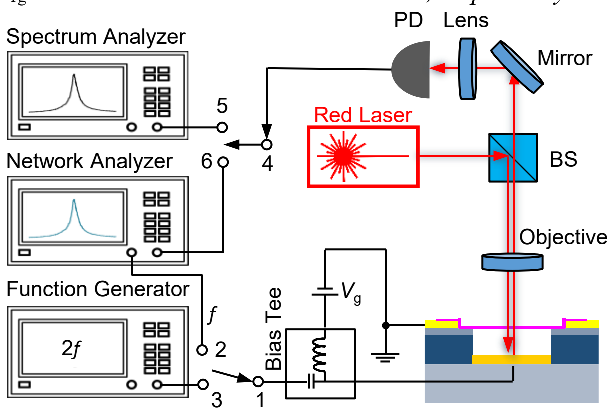

Figure 3: Illustration of the measurement scheme, showing how the driven resonance (connect nodes 1,2 and 4,6) and undriven thermomechanical noise spectral density (connect nodes 4,5) are measured. The pump signal is introduced to the local gate using a function generator (connect nodes 1,3). PD: photodetector, BS: beam splitter.

MEASUREMENT AND ANALYSIS

Resonance motion of the 2D NEMS resonator under electrical parametric pumping can be described by

$$m\ddot{x} + \frac{m\omega\dot{x}}{Q} + [k_1 + k_\mathrm{p}\cos(2\omega t)]x + k_3x^3 = F(t), \quad (1)$$

where x, t, m, ω, k_1, k_3, and $F(t)$ are displacement, time, effective mass, angular frequency at resonance (ω=2πf), linear spring constant, third order spring constant, and driving force, respectively. $F(t)$ can be either a harmonic drive with amplitude proportional to v_{drv} and frequency f_{drv} or thermal noise. The periodic modulation of linear stiffness at $2f$ is described by $k_\mathrm{p}\cos(2\omega t)$, where k_p indicates the electrical pump strength. The atomically thin MoS_2 2D

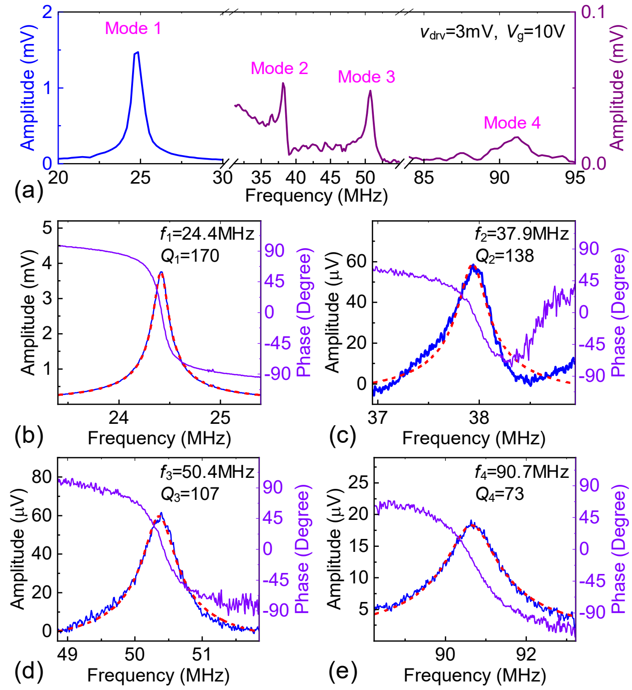

Figure 4: (a) Multimode resonances from a single-layer (1L) MoS_2 drumhead in a wide spectrum showing 4 distinct resonance modes measured. Driven resonance of the (b) 1st, (c) 2nd, (d) 3rd, and (e) 4th mode with Qs of 170, 138, 107, and 73, respectively. Blue and red curves show the measured data and fitting curves, respectively.

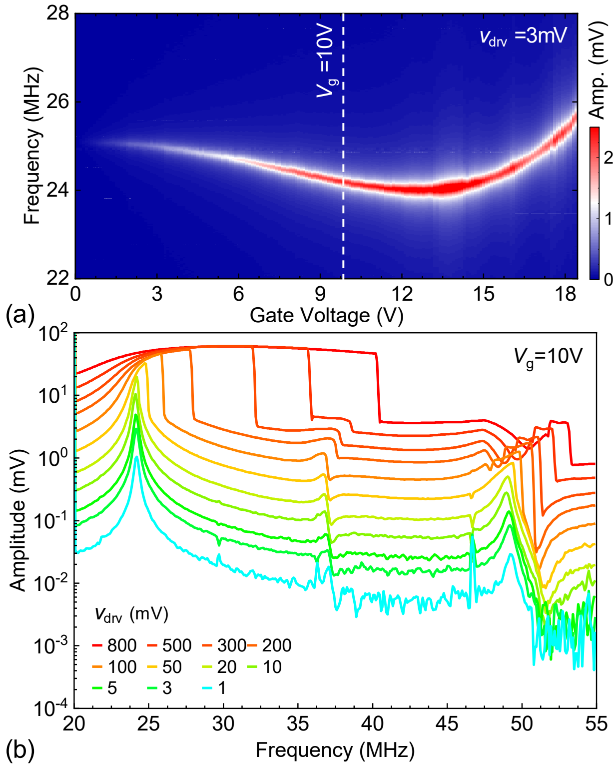

Figure 5: (a) Frequency tuning with V_g=0 to 18.5V, while at v_{drv}=3mV. (b) Duffing responses (up sweep) measured from the 1L MoS_2 device by varying v_{drv} (at V_g=10V).

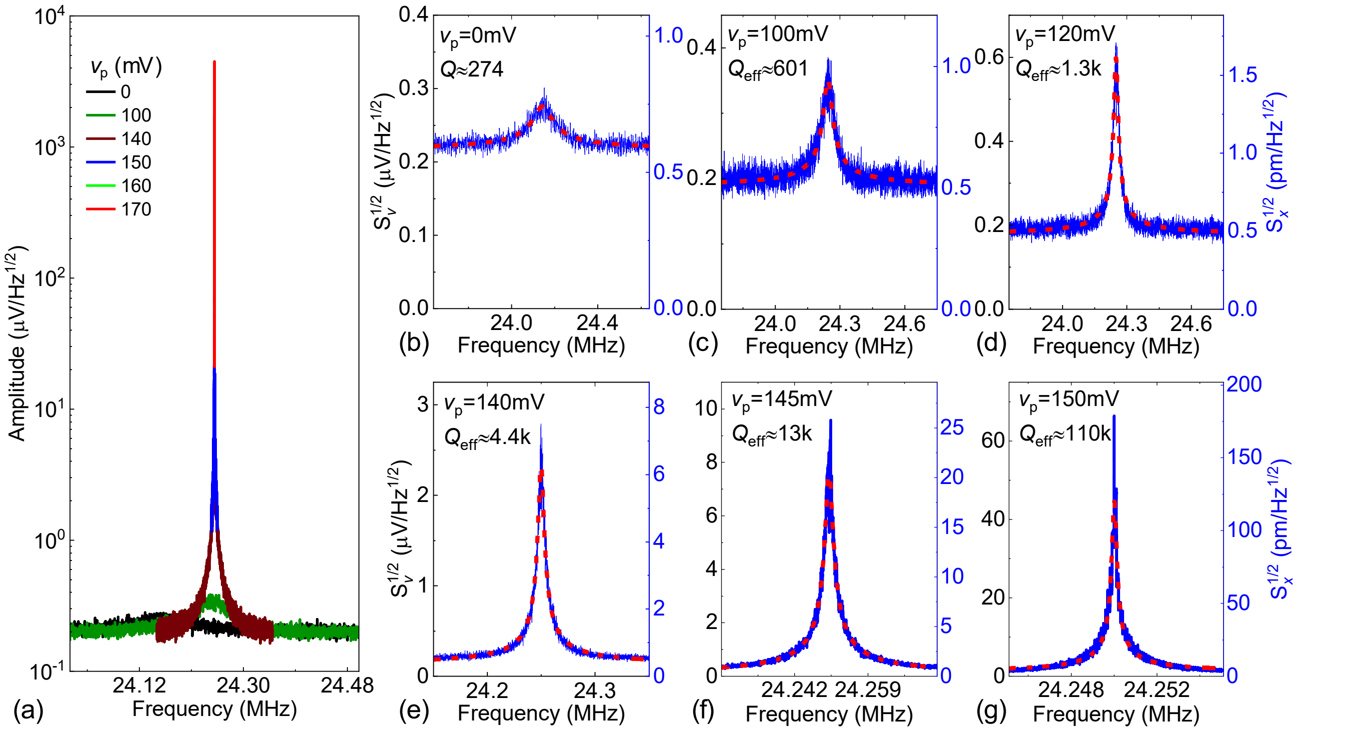

Figure 6: (a) Measured noise spectral density of the 1L MoS_2 device at varying pump voltage. (b) Thermomechanical noise measurement without parametric pumping. Measured resonances with pump voltages at (c)100mV, (d) 120mV, (e) 140mV, (f) 145mV, and (g) 150mV, respectively. Red dashed curves are obtained by fitting the measured data (blue curves).

drumhead with low linear stiffness (k_1) operating in the tension dominated regime can be efficiently pumped with electrical pump voltage via the local gate.

Therefore, we electrically parametrically pump the 1L MoS_2 resonator at twice the fundamental mode frequency using a function generator and record the corresponding spectrum using a spectrum analyzer (Fig. 3). A network analyzer is used to measure the driven resonance. Applied DC voltage (V_g) to local gate enables tuning the resonance frequency of the 2D NEMS resonator. The PnFC is generated by driving the device near $2f$, establishing 2:1 mode coupling in the multimode MoS_2 resonator.

RESULTS AND DISCUSSIONS

We first excite the device by applying a 10V DC gate voltage (V_g) and 3mV RF drive (v_{drv}) to the local gate and measure 4 driven resonance modes at 24.4MHz, 37.9MHz, 50.4MHz, and 90.7MHz, with Qs of 170, 138, 107, and 73, respectively (Fig. 4). Mode 1 shows clear frequency tuning for varying V_g from 0 to 18.5V. Capacitive softening dominates up to V_g≈13V showing a frequency downshift; tension-induced stiffening dominates when V_g>13V, exhibiting frequency upshift. The device responses show clear Duffing nonlinearity with increasing v_{drv} (Fig. 5). The measured thermomechanical noise for mode 1 shows a resonance frequency of 24.14MHz with Q≈274. The responsivity of the system, defined as the ratio of the voltage domain thermomechanical noise spectral density $S_v^{1/2}$ to displacement domain thermomechanical noise spectral density $S_{th}^{1/2}$, is 0.371μV/pm at room temperature. After characterizing the undriven resonance of the drumhead, we pump the device at $2f$ using RF pump voltage (v_p) from a function generator, starting from 10mV to 170mV, and record the corresponding noise spectral

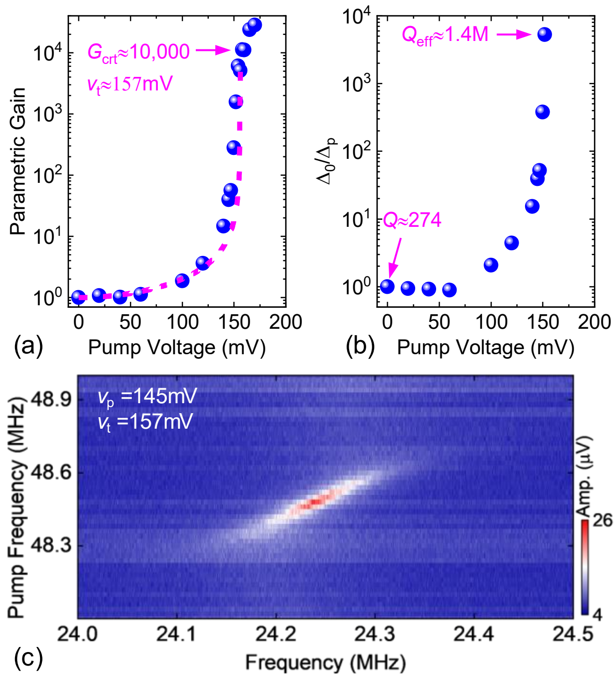

Figure 7: Measured (a) parametric gain and (b) Δ_0/Δ_p at varying pump voltage, showing giant gain and spectral narrowing due to electrical pump. (c) Measured pumped thermomechanical noise with varying f_p at v_p=145mV.

density near the resonance. Figure 6 shows a series of thermomechanical noise spectra measured at various pump voltages. At low v_p, the thermomechanical noise spectrum slowly starts to increase with increasing pump strength. When v_p approaches the threshold pump voltage (v_t), the thermomechanical resonance shows giant amplification with exceptional spectral linewidth narrowing. Parametric pumping below v_t can be described by the equation

$$G = \frac{S_{x,\text{pump}}^{1/2}(\omega_0)}{S_x^{1/2}(\omega_0)} = \sqrt{\left[1+\left(\frac{v_p^2}{v_t^2}\right)\right] \Big/ \left[1-\left(\frac{v_p^2}{v_t^2}\right)\right]}, \quad (2)$$

where G is the parametric gain [6] and $S_{x,\text{pump}}^{1/2}(\omega_0)$ and $S_x^{1/2}(\omega_0)$ are the spectral peak with and without parametric pumping. Fitting the data to Eq. (2), we obtain a parametric threshold $v_t \approx 157$mV and critical gain $G_{crt} \approx 10{,}000$ (80dB).

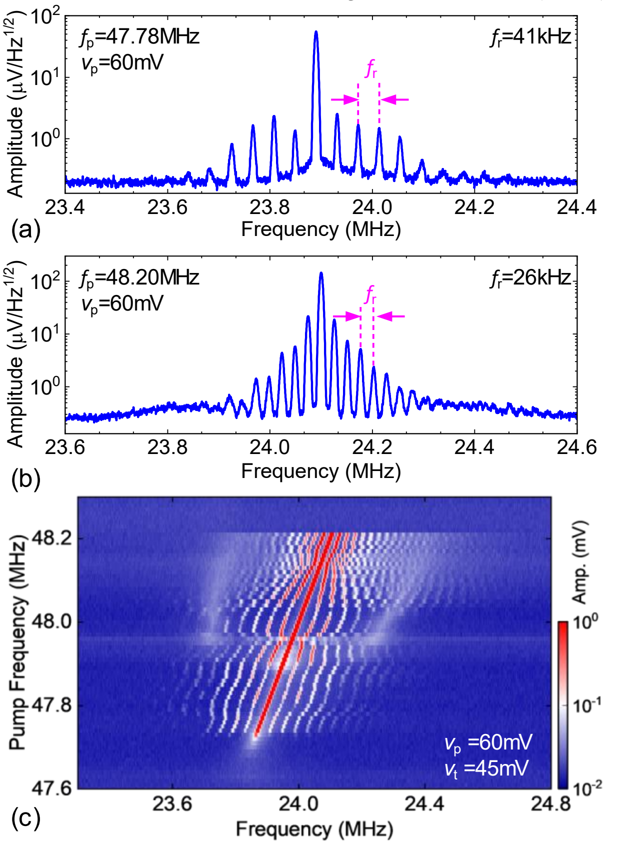

Figure 8: Phononic frequency comb generation by driving a new MoS_2 device at (a) 47.78MHz and (b) 48.2MHz, with comb spacing f_r=41kHz and 26kHz, respectively. (c) Evolution of phononic frequency comb by varying the pump frequency with v_p=60mV (for calibrated v_t=45mV).

The linewidth of noise spectral density also drops sharply near v_t due to spectral narrowing. With v_p=153mV, the parametric gain reaches up to ~10,000 (80dB) and the linewidth narrowing factor (Δ_0/Δ_p) reaches ~5000. We cannot reliably capture the linewidth narrowing beyond v_p=153mV due to the 1Hz resolution bandwidth limit imposed by the instrument. Sweeping the pump frequency (f_p) with fixed v_p=145mV reveals a range for f_p that can parametrically pump the resonator, as shown in Fig. 7c with spectrum analyzer measurements.

The multimodal MoS_2 drumhead resonator exhibits a 3rd mode (Fig. 4a) that lies within the parametric pump range near 2f. As we vary the pump frequency, the 2:1 internal resonance condition is satisfied, leading to generation of phononic frequency comb in frequency domain with tunable comb spacing. As captured in careful spectrum analyzer measurements, pumping the device at f_p=47.78MHz with v_p=60mV generates a comb with spacing f_r=41kHz (Fig. 8a). When f_p=48.2MHz, the comb spacing changes to f_r=26kHz (Fig. 8b). Figure 8c shows the evolution of the comb spacing and number of teeth with varying pump frequency. Generated PnFC spacing can be further tuned by controlling the pump strength.

CONCLUSION

In summary, we have experimentally demonstrated highly efficient electrical parametric amplification by directly pumping on undriven thermomechanical noise spectra. We have achieved giant parametric amplification up to ~80dB, and exceptional spectral linewidth narrowing factor ~5000. Driving the device parametrically near its 3rd mode (close to 2f) to establish 2:1 internal resonance enables mode coupling, thus leading to PnFC generation. The observed frequency comb spacing can be tuned by varying pump frequency f_p and voltage v_p. The findings here shall contribute towards building high-performance NEMS for sensing in classical and quantum applications.

ACKNOWLEDGEMENTS

We thank the financial support from NSF (Grants: 2142552, 2103091) at University of Florida. S. W. Shaw is partly supported by BSF (Grant 2018041) at Florida Tech.

REFERENCES

[1] J. Lee, Z. Wang, K. He, R. Yang, J. Shan, P. X.-L. Feng, "Electrically Tunable Single- and Few-Layer MoS_2 Nanoelectromechanical Systems with Broad Dynamic Range", *Sci. Adv.* **4**, eaao6653, 2018.

[2] F. Ye, A. Islam, T. Zhang, P. X.-L. Feng, "Ultrawide Frequency Tuning of Atomic Layer van der Waals Heterostructure Electromechanical Resonators", *Nano Lett.* **21**, 5508-5515, 2021.

[3] P. Prasad, N. Arora, A. K. Naik, "Parametric Amplification in MoS_2 Drum Resonator", *Nanoscale* **9**, 18299-18304, 2017.

[4] R. J. Dolleman, S. Houri, A. Chandrashekar, F. Alijani, H. S. J. van der Zant, P. G. Steeneken, "Opto-Thermally Excited Multimode Parametric Resonance in Graphene Membranes", *Sci. Rep*. **8**, 9366, 2018.

[5] R. Singh, R. J. T. Nicholl, K. I. Bolotin, S. Ghosh, "Motion Transduction with Thermo-Mechanically Squeezed Graphene Resonator Modes", *Nano Lett*. **18**, 6719-6724, 2018.

[6] J. Lee, S. W. Shaw, P. X.-L. Feng, "Giant Parametric Amplification and Spectral Narrowing in Atomically Thin MoS_2 Nanomechanical Resonators", *Appl. Phys. Rev.* **9**, 011404, 2022.

[7] A. Ganesan, C. Do, A. Seshia, "Phononic Frequency Comb via Intrinsic Three-Wave Mixing", *Phys. Rev. Lett.* **118**, 033903, 2017.

[8] J. Lee, S. W. Shaw, P. X.-L. Feng, "Phononic Frequency Comb Generation via 1:1 Mode Coupling in MoS_2 2D Nanoelectromechanical Resonators", in *Proc. of the 35th IEEE Int. Conf. on Micro Electro Mechanical Systems (MEMS 2022)*, Tokyo, Japan, January 9-13, 503-506, 2022.

CONTACT

*S M Enamul Hoque Yousuf: syousuf@ufl.edu
*Yunong Wang: yunongwang@ufl.edu
*Philip Feng: philip.feng@ufl.edu