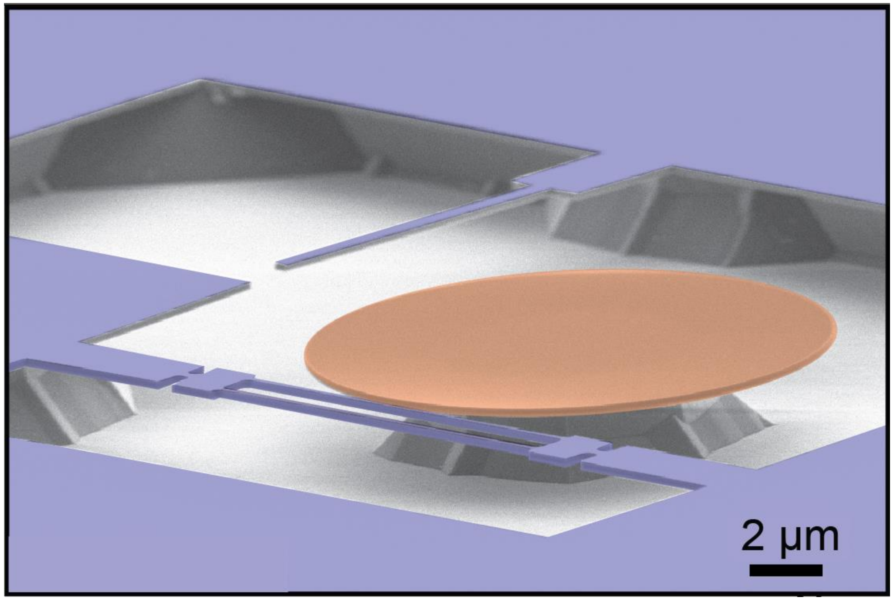
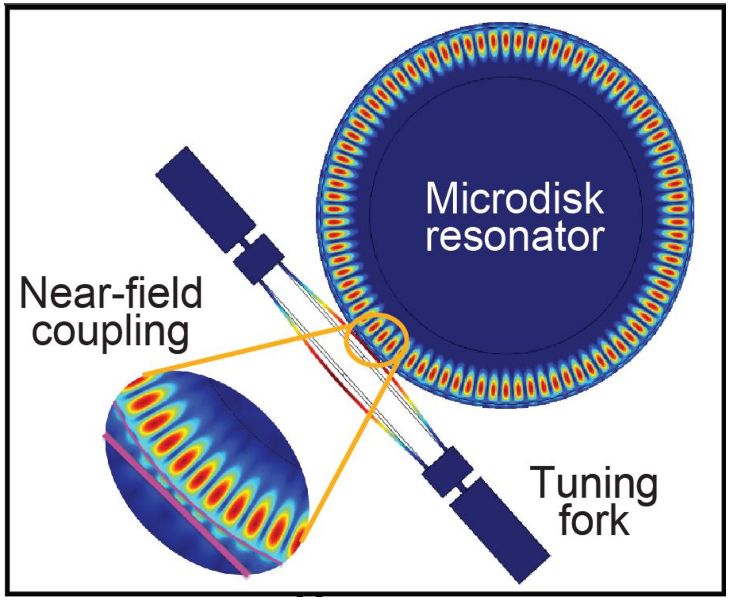
High mechanical $f_m Q_m$ product tuning fork cavity optomechanical transducers





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NIST National Institute of Standards and Technology U.S. Department of Commerce

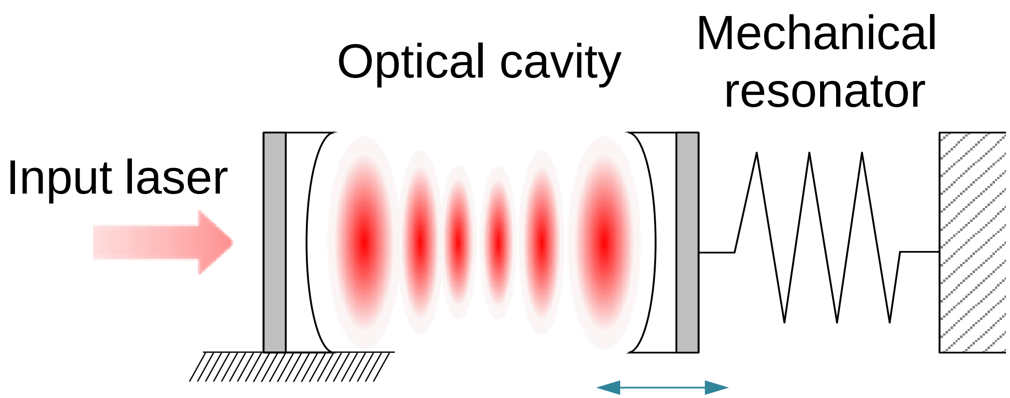
CNST Center for Nanoscale Science & Technology

Worcester Polytechnic Institute

Outline

- Background
  - Cavity optomechanics
  - Cantilever-based optomeachanical transducers
- Motivation
- Device working principles, and test results
  - Near-field optomechanical readout
  - Geometry-determined resonant frequency
  - Temperature compensation
- Summary and future work

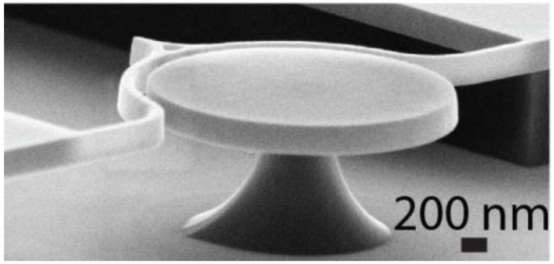
Cavity Optomechanics



Mechanical motion → Change in cavity effective length → Near-field Optomechanical readout

Change in cavity effective length → Radiation pressure

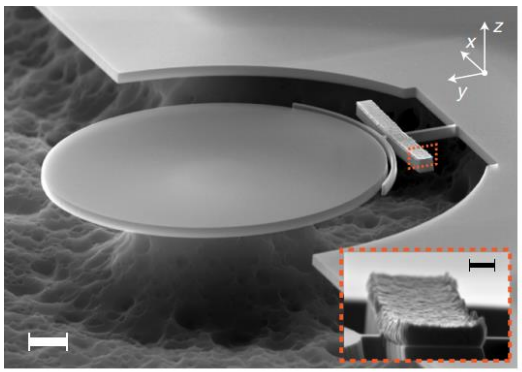
Radiation pressure → Backaction → Mechanical motion



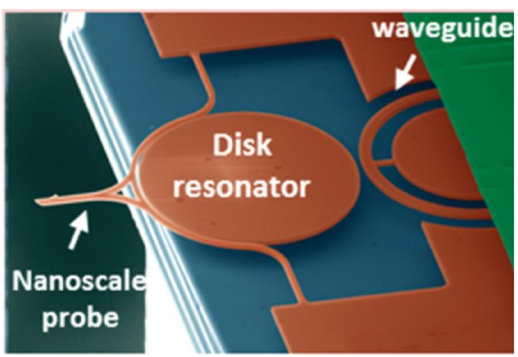
Opt. Express 20, 18268 (2012)

Cantilever-based Si_3N_4 Devices

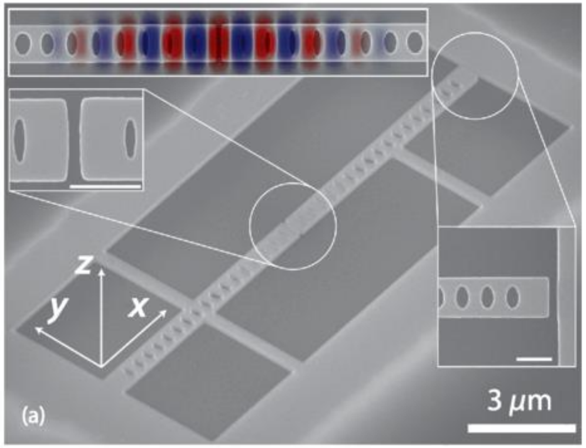
- Cantilever-based optomechanical devices
  - Separation between optical and mechanical resonator
  - Small mass
    - Moderate fundamental mechanical frequencies (MHz)
    - High sensitivity



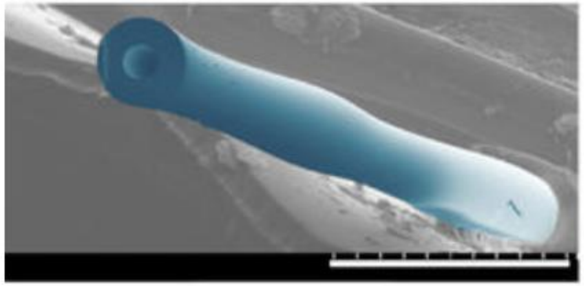
Nat. Commun. 1355 (2017)



Nano Lett., 2017, 17 (9), pp 5587–5594



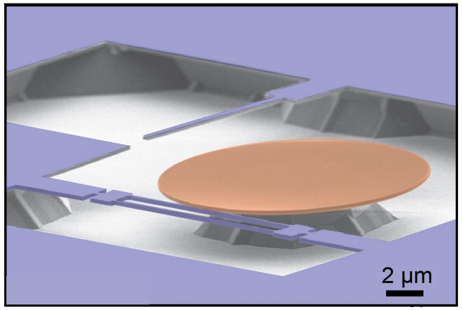
Phys. Rev. X 4, 021052

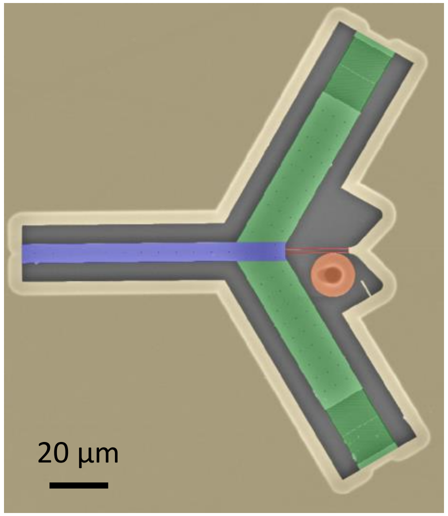


Nat. Commun. 1994 (2013)

Motivation

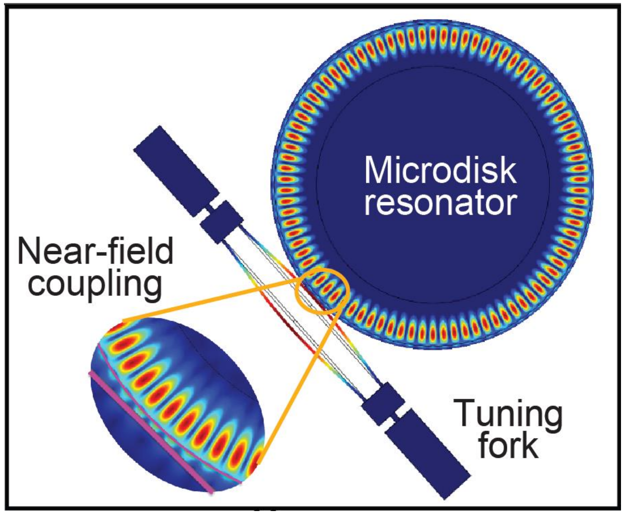
To develop a high-precision, low-drift displacement measurement platform for various precision MEMS sensor applications

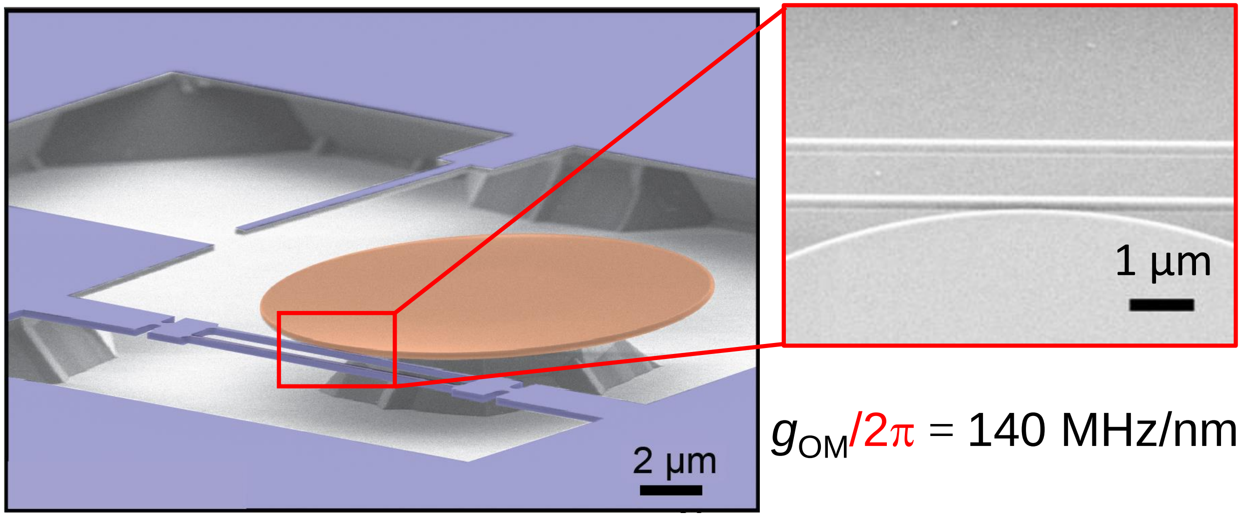




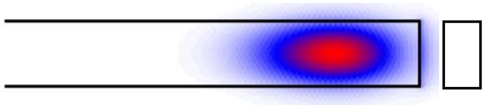
- Enhanced transduction at small scales
  - Frequency stability and limit of detection: $\langle \delta f/f0 \rangle = (1/2Q)10^{-(DR/20)}$
- High mechanical $f_m Q_m$ product
  - High bandwidth
  - Force sensitivity scales as $1/(f_m^{0.5} Q_m^{0.5})$
  - Overcome tradeoff betwee f_m and Q_m
- Si_3N_4 mechanical resonator with design-determined mechanical frequency
  - Si_3N_4 intrinsic stress varies with different fabrication processes
- Mechanical resonator with design-enabled temperature compensation
  - Remove influence from temperature
  - Not rely on matching different materials/in-situ active temperature control.
- Solution:
  - Tuning fork optomechanical transducer with near-field readout and special nonlinear mechanical clamp design.

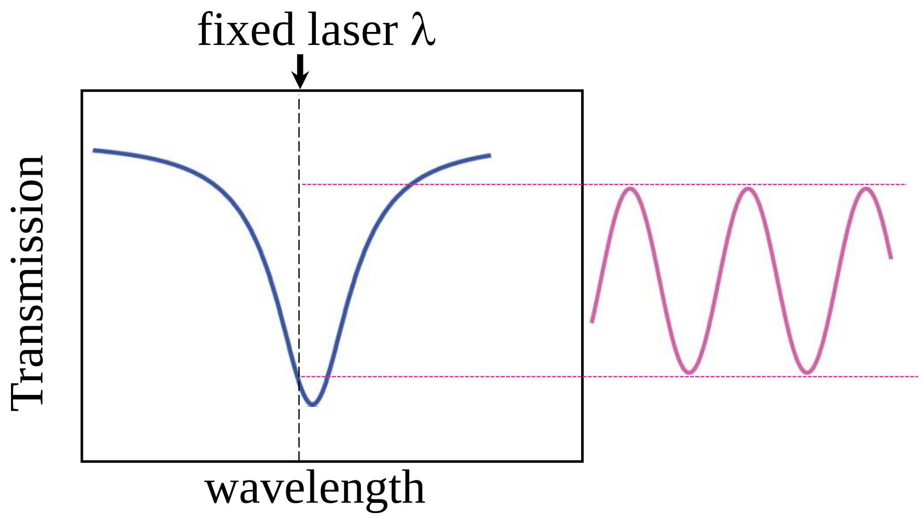
Near-field Optomechanical Readout



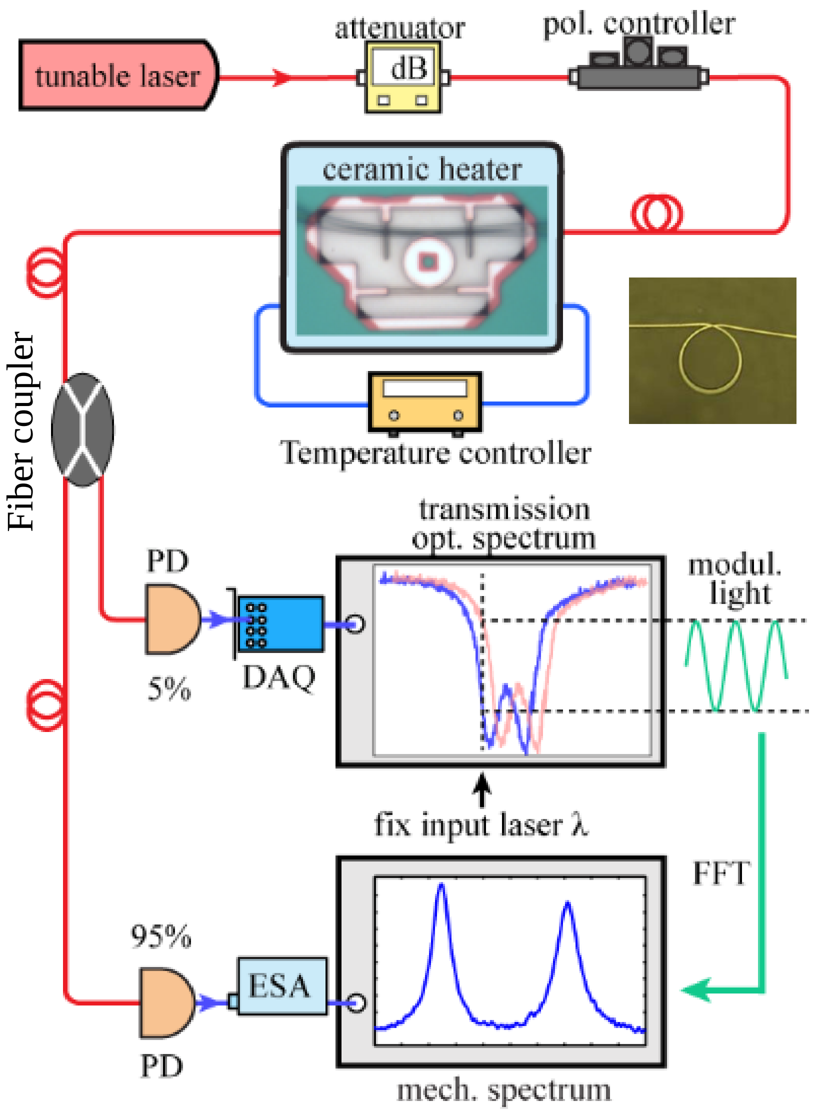


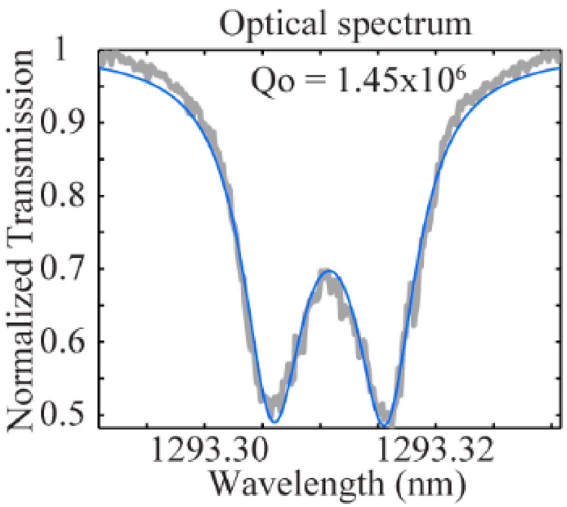
$g_{OM}/2\pi$ = 140 MHz/nm

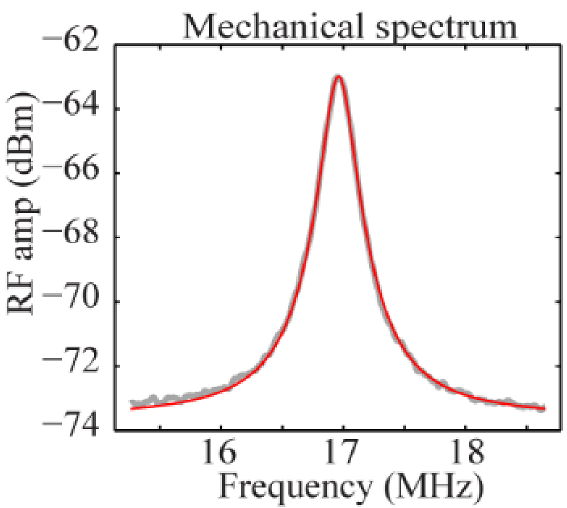




Device Characterization Setup



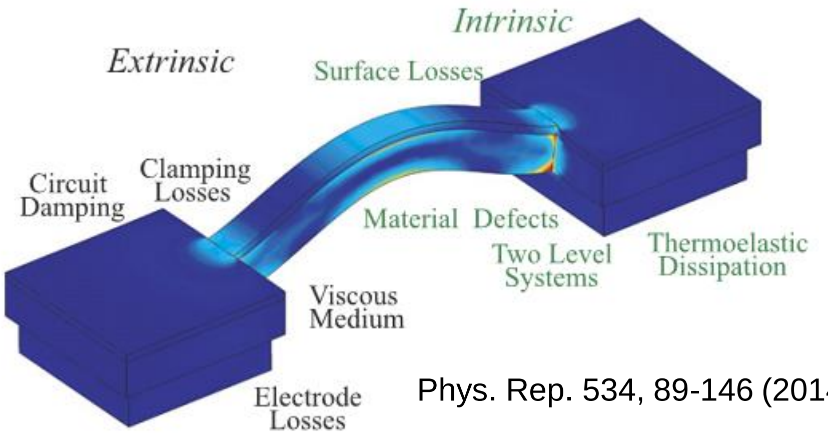




Random motion of a resonator driven by thermomechanical noise can be resolved

High $f_m Q_m$ Product – Tuning fork

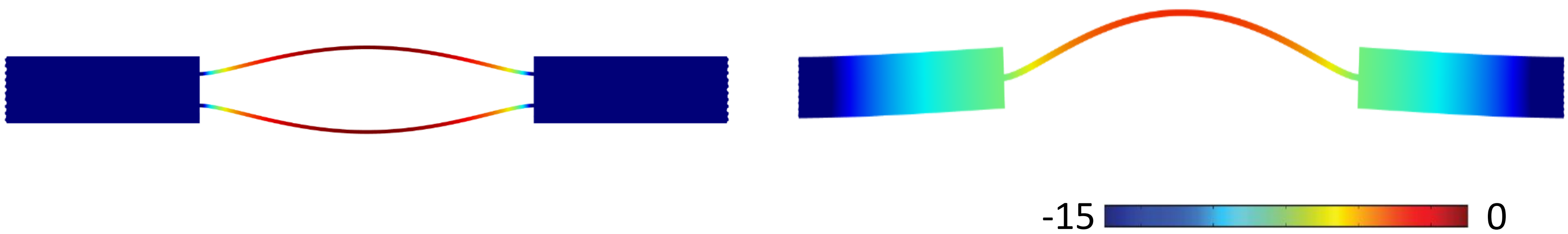
- Loss for mechanical resonators operating in vacuum
  - Thermoelastic dissipation (TED)
  - Material loss
    - Volume loss
    - Surface loss
  - Clamping loss



Phys. Rep. 534, 89-146 (2014)

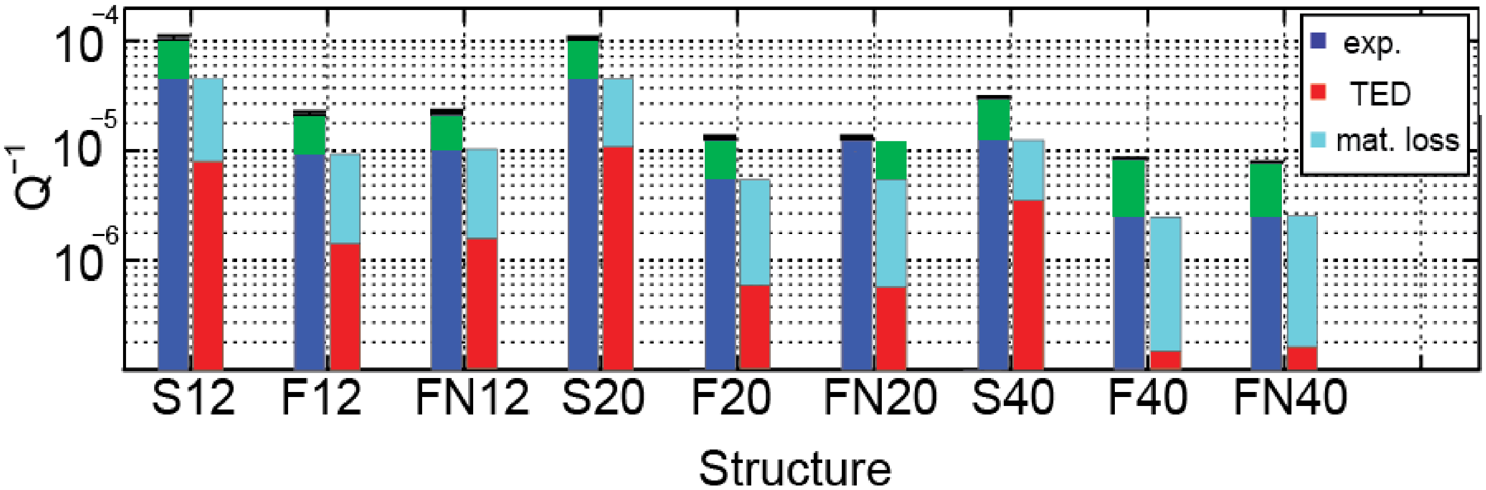
$$1/Q_M = 1/Q_{clamiping} + 1/Q_{TED} + 1/Q_{material} + 1/Q_{other}$$

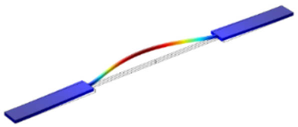
All these losses can be reduced by localized motion



Logarithmic scale normalized displacement

Localized Motion Reduces Mechanical Loss



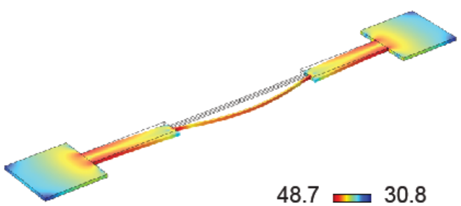


S: single beam

F: tuning fork

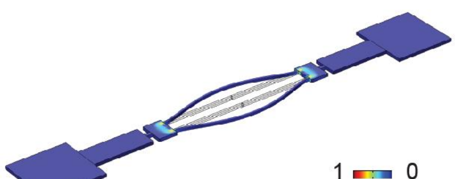
FN: tuning fork with neck

Normalized temparature gradient

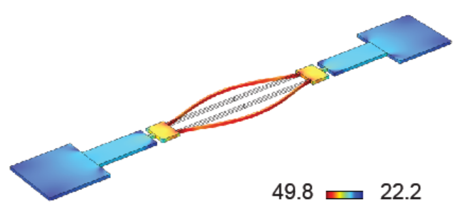


Logarithmic scale elastic strain energy density

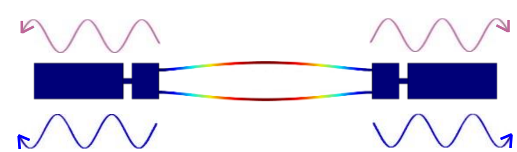
$$1/Q_{clamping} \approx 1/Q_M - 1/Q_{TED} - 1/Q_{material}$$



Normalized temparature gradient

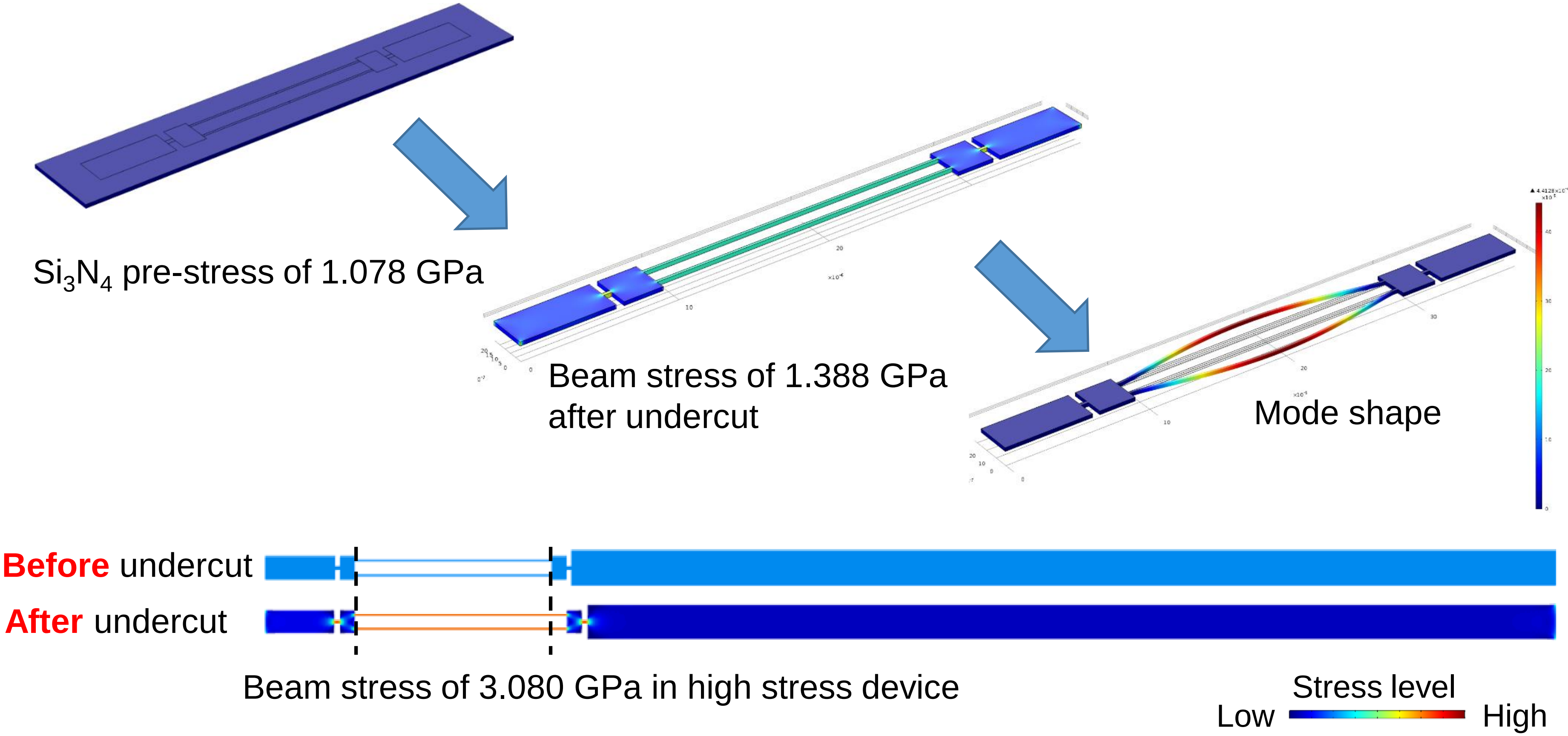


Logarithmic scale elastic strain energy density

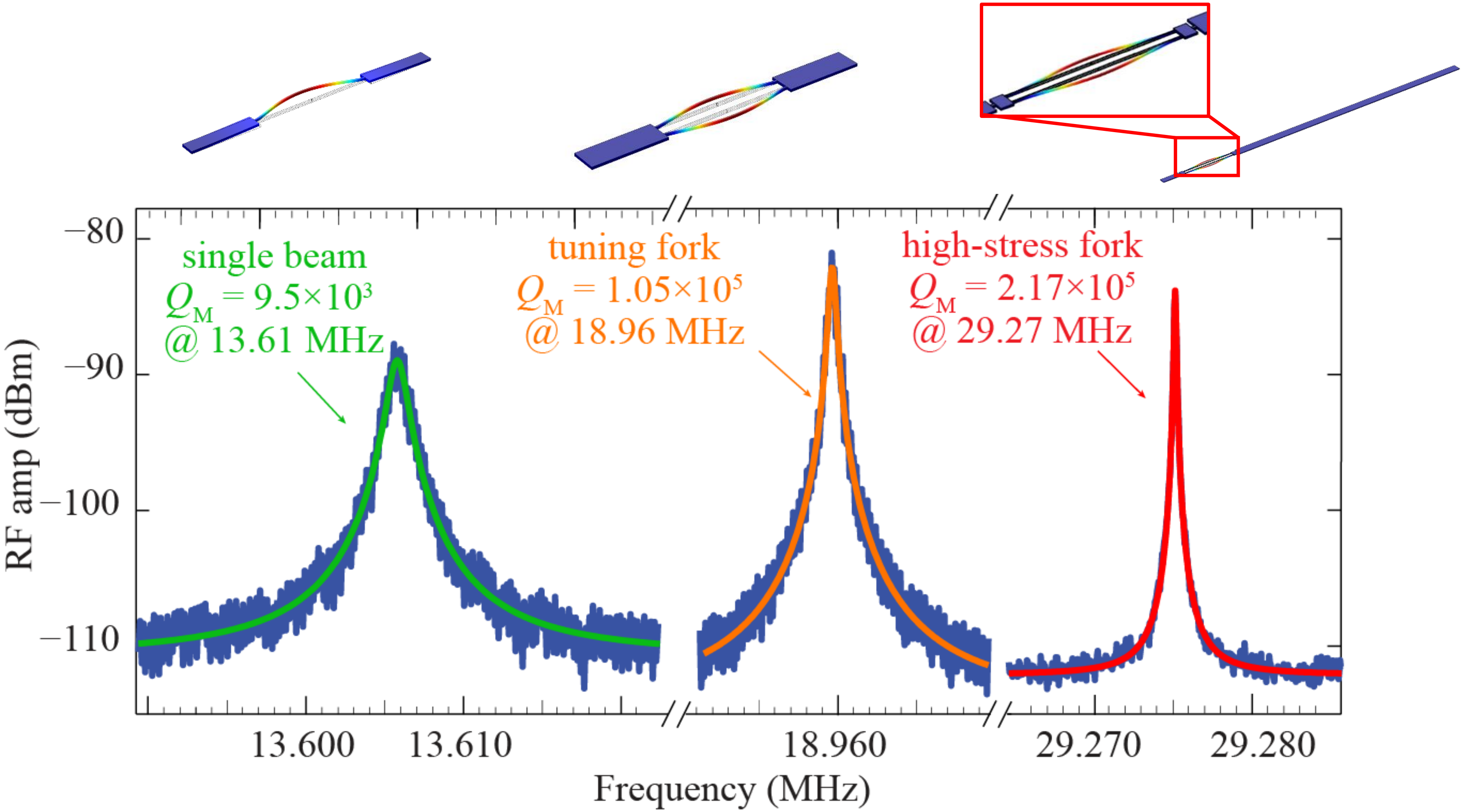


Stress Engineering

- Doubly clamped Si_3N_4 tuning forks with a high tensile stress
  - LPCVD Si_3N_4 has high intrinsic tensile stress uniformly distributed
  - The stress retained with doubly clamped tuning forks but redistributed
  - Final beam stress/frequency can be engineered without reduction of Q_m

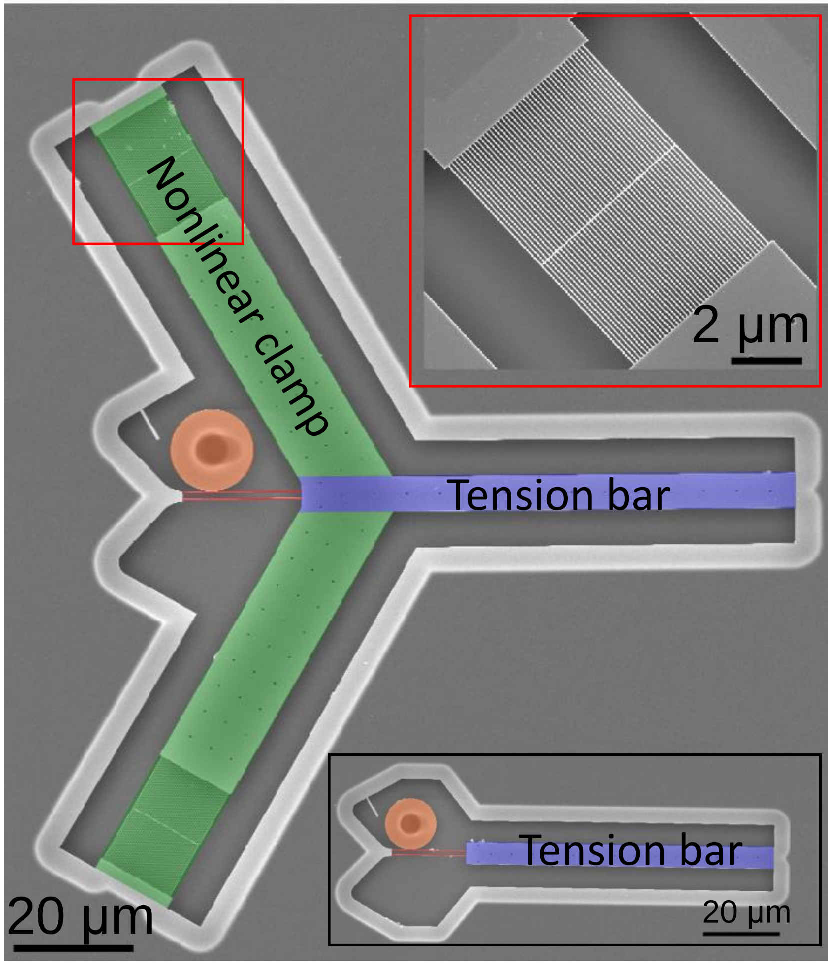


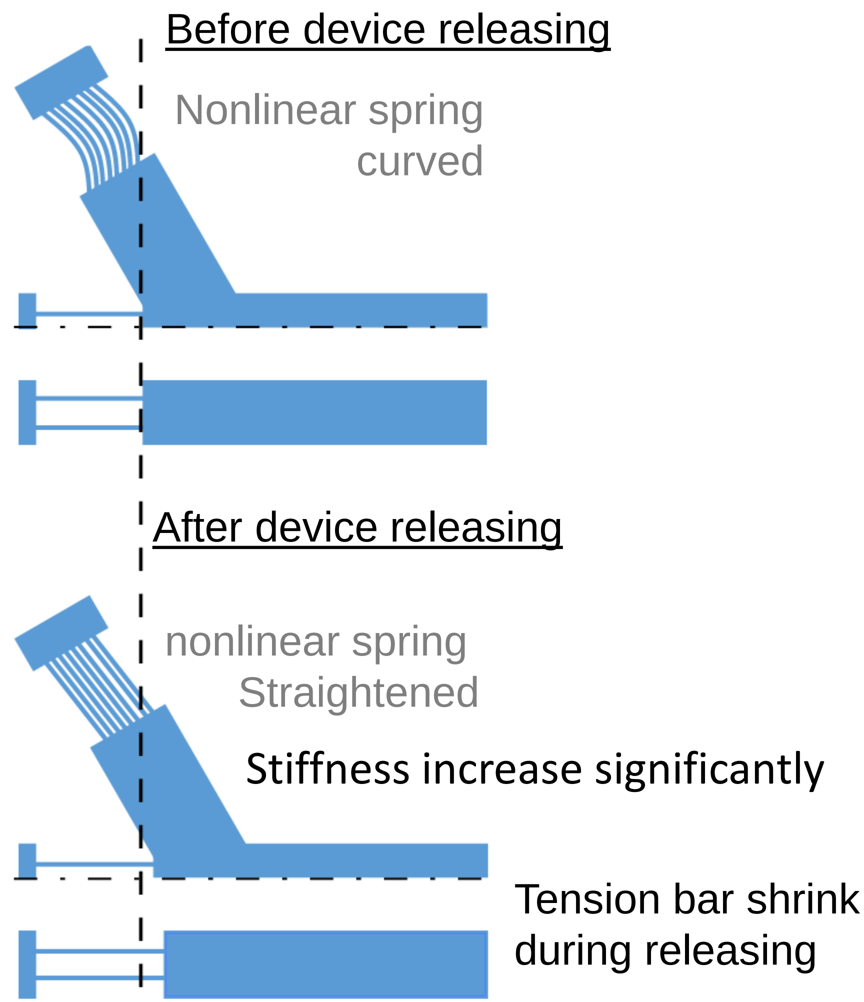
Measured Mechanical Spectra



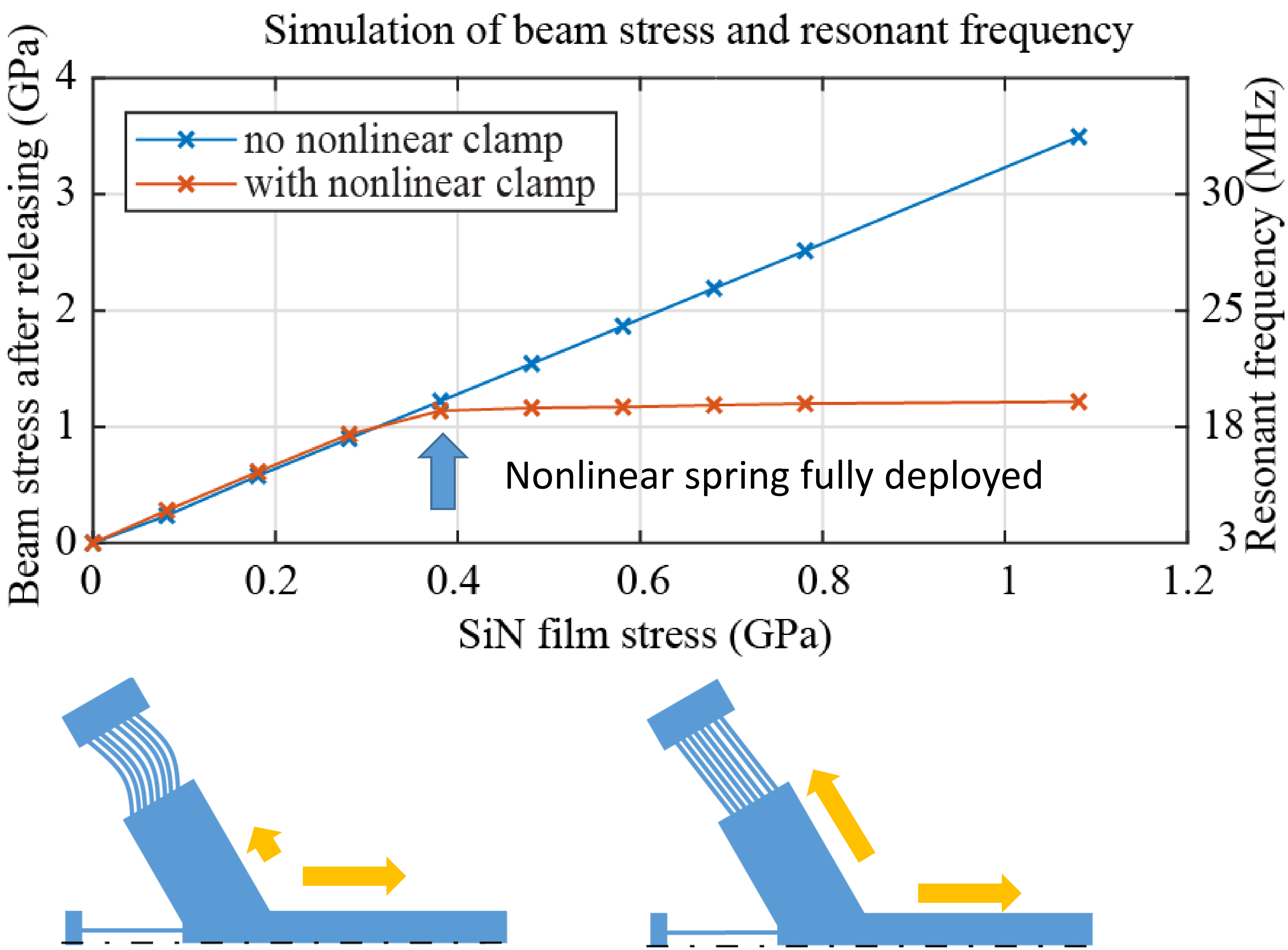
Stress Engineering – More Controllable?

- Nonlinear clamp design enable the frequency only determined by geometry
  - In regular tuning fork, the final beam stress/frequency determined by both intrinsic stress and the geometry



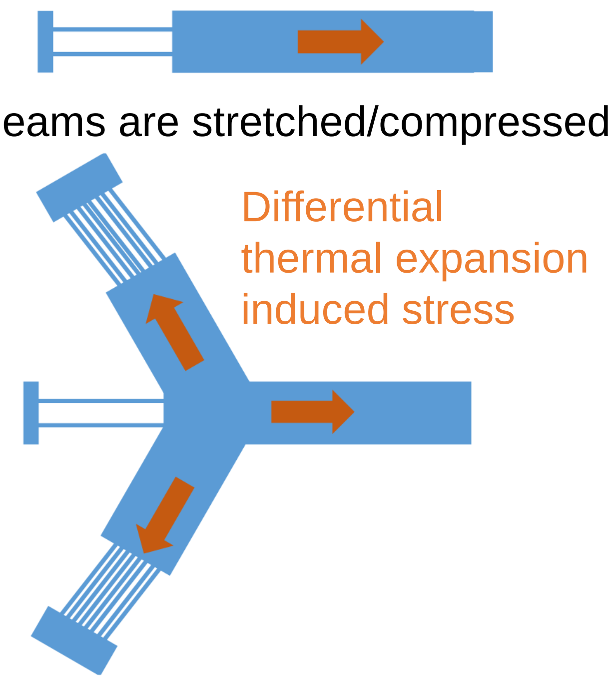


Stress Engineering – More Controllable?



Temperature compensation

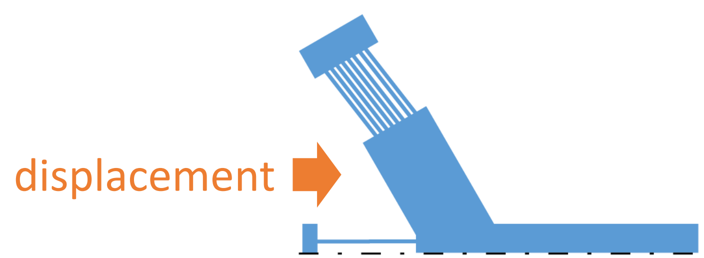
- With similar working principles, temperature sensitivity of vibration frequencies can also be engineered.
  - Temperature induced frequency fluctuation is mainly due to thermal expansion mismatch between device layer and substrate
  - Coefficient of Thermal Expansion (CTE) of Si: 2.6×10^{-6} (K^{-1})
  - CTE of LPCVD Si_3N_4: 1.6×10^{-6} (K^{-1})



Beams length remain fixed

Allan deviation measurement

- Relative bias stability is ≈ 10^{-6} above 1 s averaging
  - Thermal dynamic limited
- Displacement uncertainty ≈ 0.2 pm



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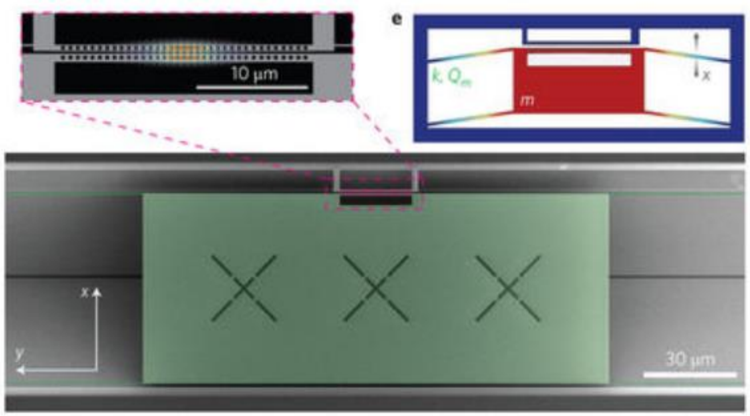
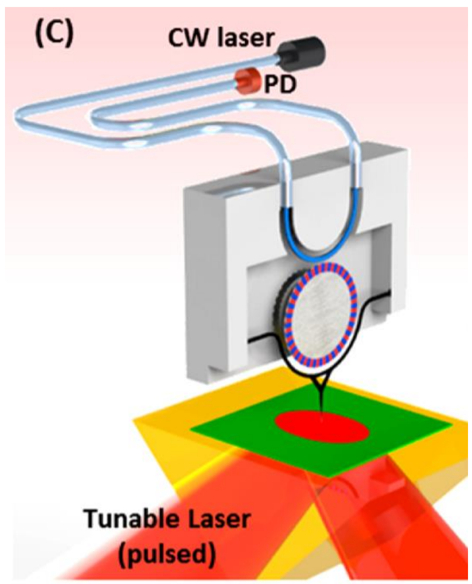
Summary

- Doubly clamped Si_3N_4 tuning fork cavity optomechanical sensors
  - Near-field optomechanical readout
  - High $f_m Q_m$ product resulting from tuning fork structure and increased beam stress
  - Geometry determined stress/frequency tuning
  - Temperature compensation with tunable temperature sensitivity
- Further development
  - Inertia sensing
  - Fully integration with photonic integrated circuit



Nature Photonics 6(11): 768-772



Nano Letters 17(9): 5587-5594

Thanks for your attention.

Questions?