Photonic Thermometry

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NIST

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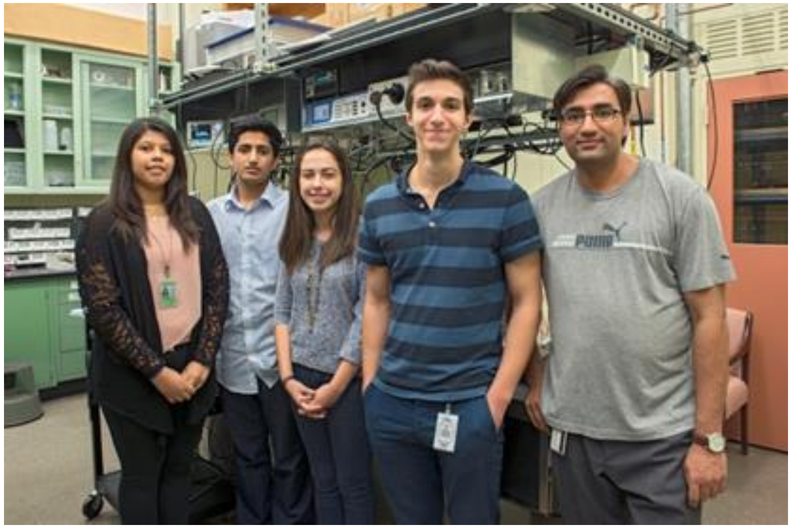


What is photonic thermometry?

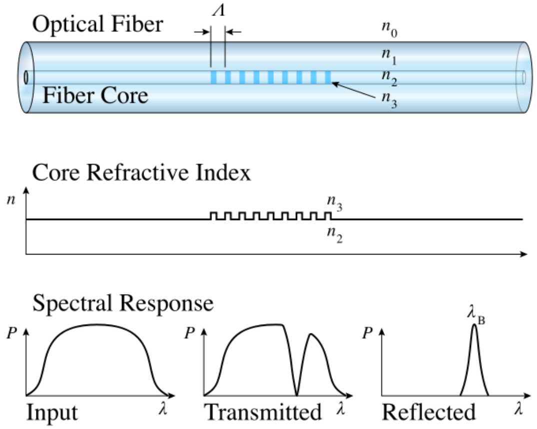
Photonic Thermometry: Use of waveguided light to exploit the thermo-optic coefficient of materials to enable highly sensitive (and accurate) temperature measurement.

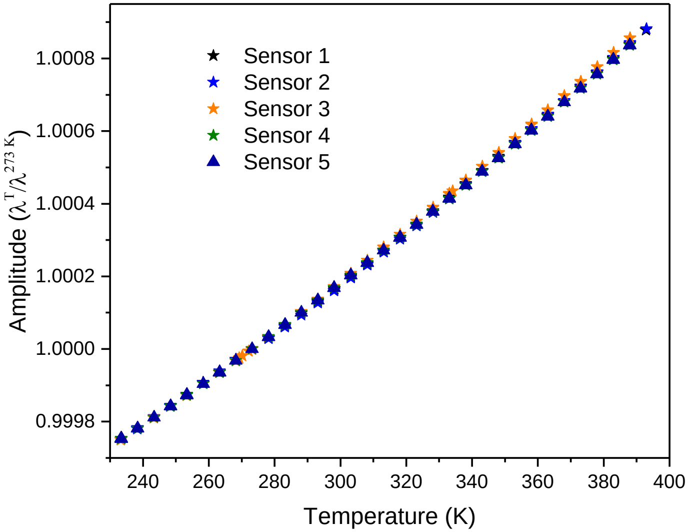
Examples of photonic thermometers range from FBG, WGMR, ring resonators, Fabry-Perot cavities and photonic crystal cavities

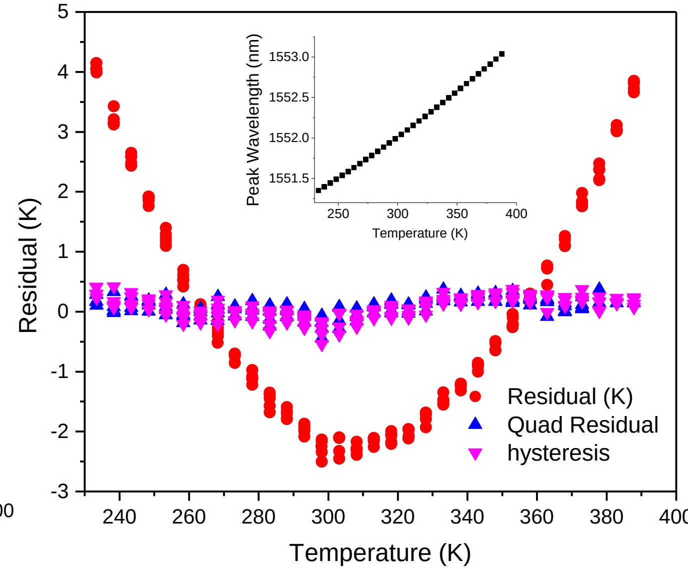
Currently the most commonly available commercial photonic thermometer is the FBG i.e. primarily used by the oil and gas, aviation and medical instrumentation fields. Manufacturing, sale and use is global spanning the Asian, North American and European continents

Companies are increasing offer ring resonator and disk resonator based sensors that can be immediately used for temperature sensing.

Fiber Bragg Gratings: A Photonic Type J Thermocouple







10 mm long sensor

Sensitivity ≈ 10 pm/K

Uncertainty ≈ 500 mK

Combined , expanded uncertainty (k=2) is 490 mK over the temperature range of 233 K to 393 K

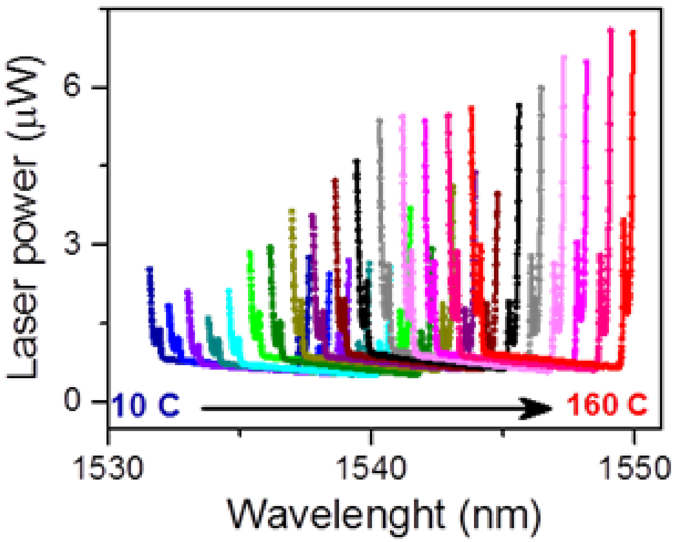
Ahmed *et. al.*; *NCSLI Measure J. Meas. Sci.*, 2015, Vol 10, pg 24-27

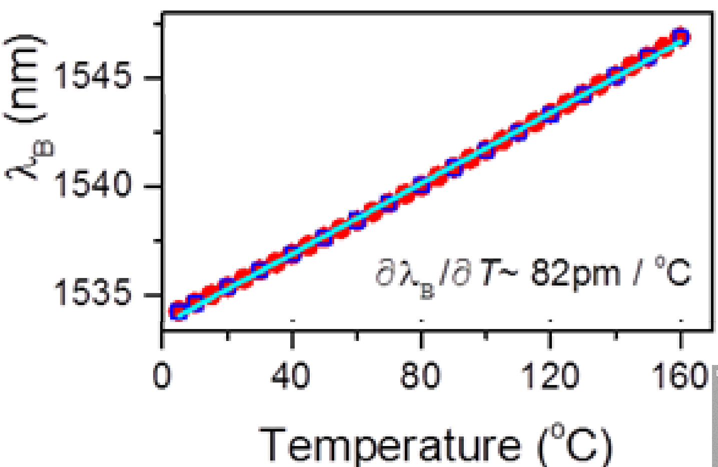
Si Bragg Thermometer shows a quadratic dependence on temperature

Silicon Bragg gratings show an ≈8x temperature sensitivity than FBG while occupying a footprint i.e 50X smaller

The uncertainty in these devices, 1.25 °C (k = 2) , is driven by uncertainty in peak center measurement.

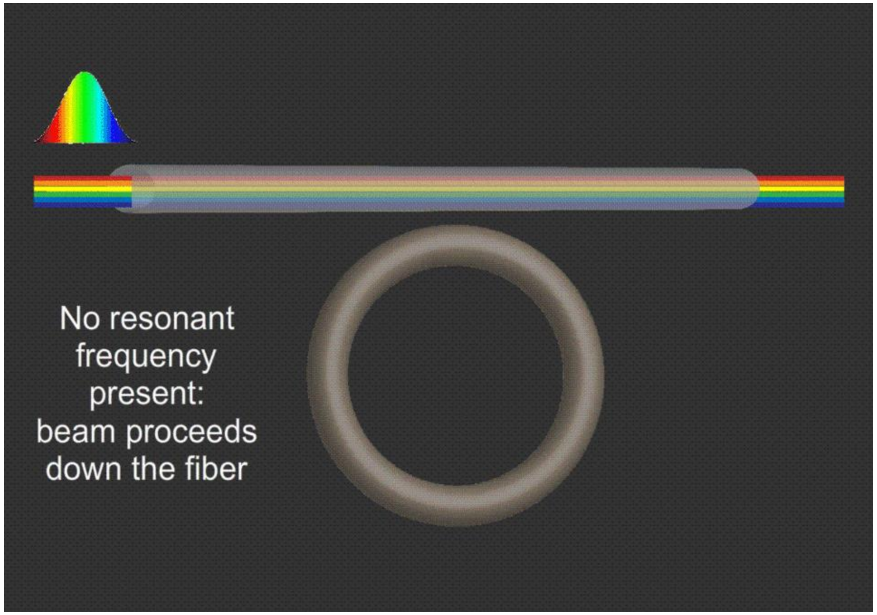
Use of higher Q devices like ring resonators and Photonic Crystal cavities can ameliorate this drawback.

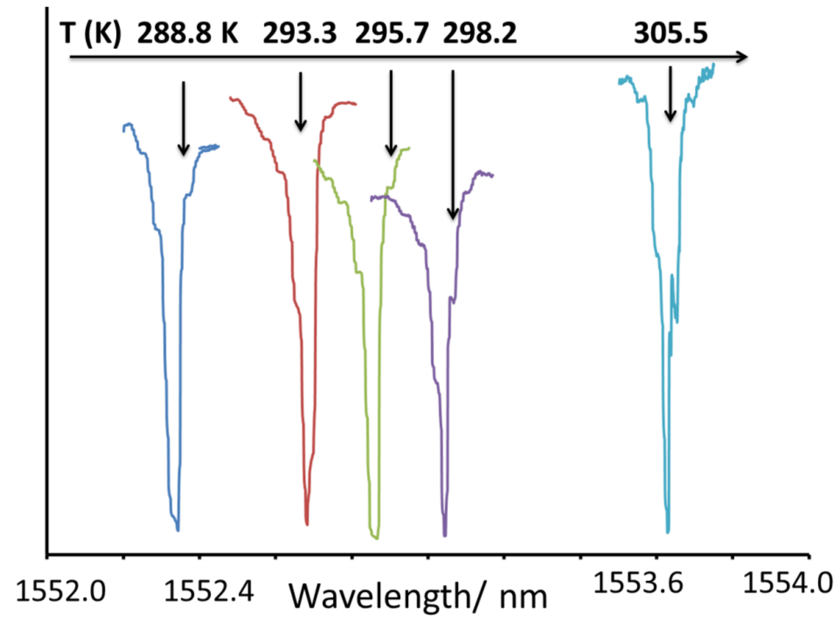




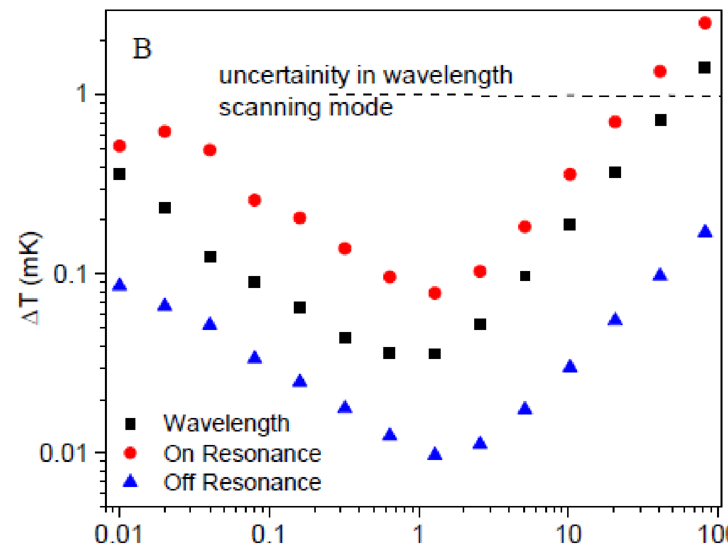
Klimov et. al.; *Optics Letters*, 2015, vol 40, pg 3934-3936

Journey of a thousand miles starts with a single step





Proof of concept experiment demonstrates the feasibility of ring resonator based thermometry; builds on the work of Kim et al (OpEx, 2010, vol 18, 22215)



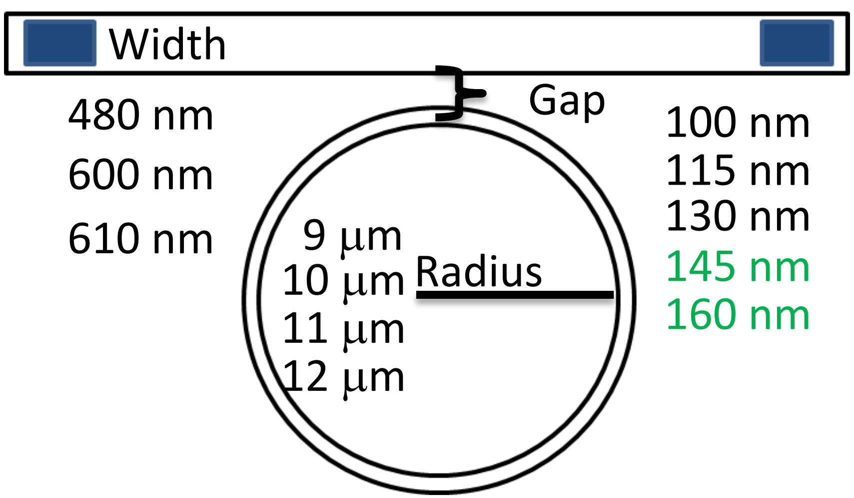
Xu et. al.; *Optics Express*, 2014, vol 22, pg 3098-3104

Photonic Device Fabrication Reproducibility

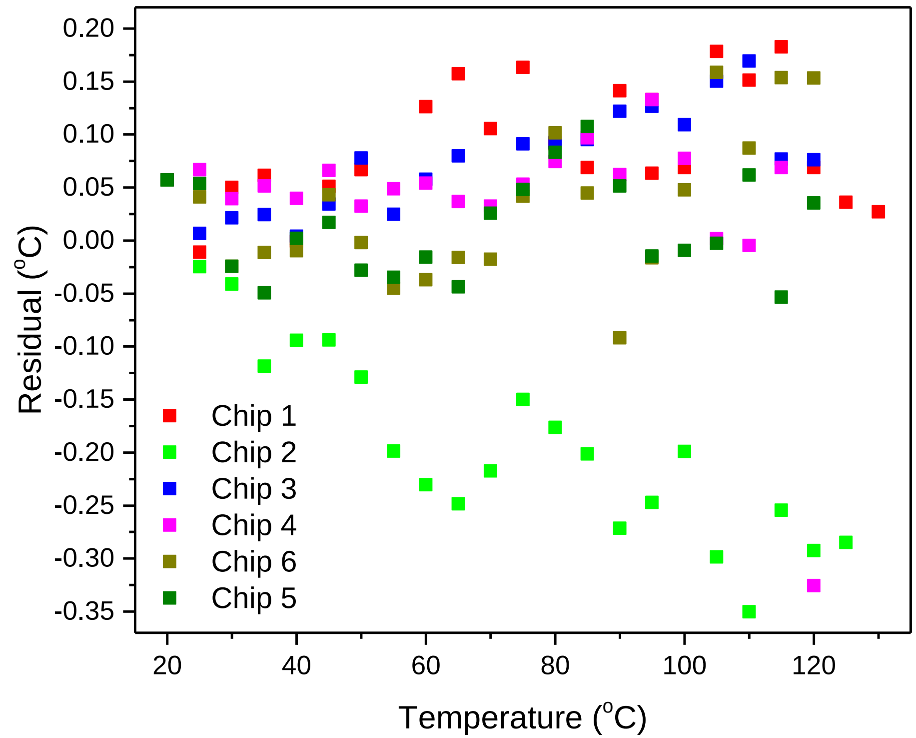
We systematically varied the structural parameters of a ring resonator in all-pass configuration, testing over 130 different configurations. Our results demonstrate a parameter space to target is:

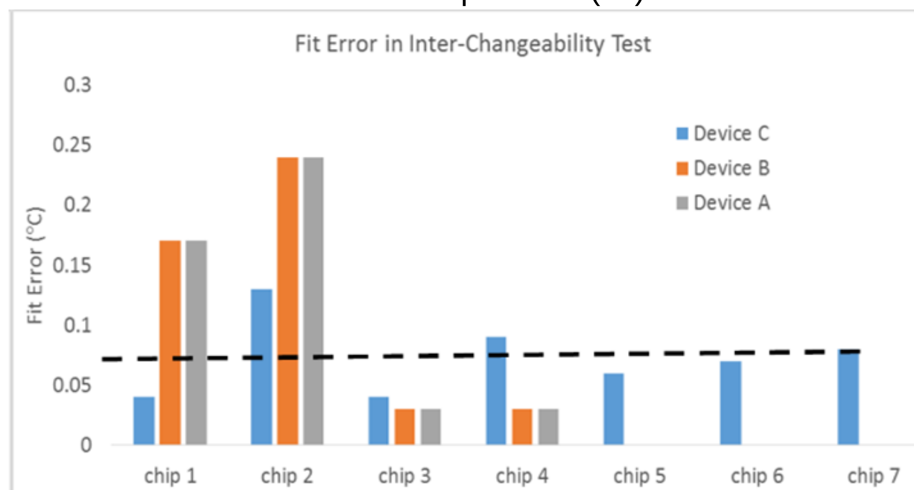
w > 600 nm, *gap* ≈130 nm and *r* >10 µm.

In this range we consistently achieve Q ≈10^4 and $\Delta\lambda/\Delta T$ ≈80 pm/K

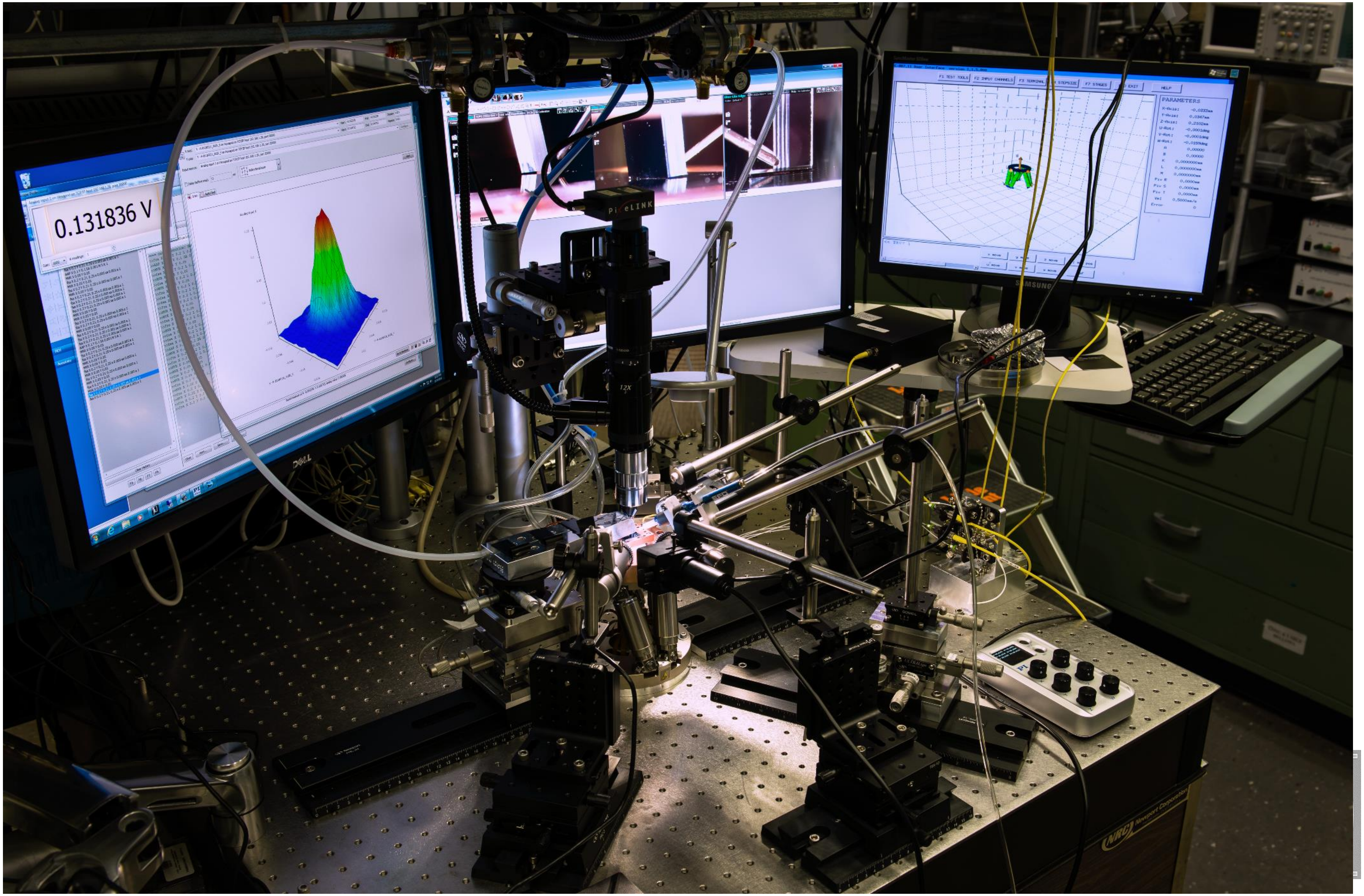


Klimov et. al.; *Sensors & Transducers*, 2015, vol 191, pg 63





In-House Sensor Packaging capabilities



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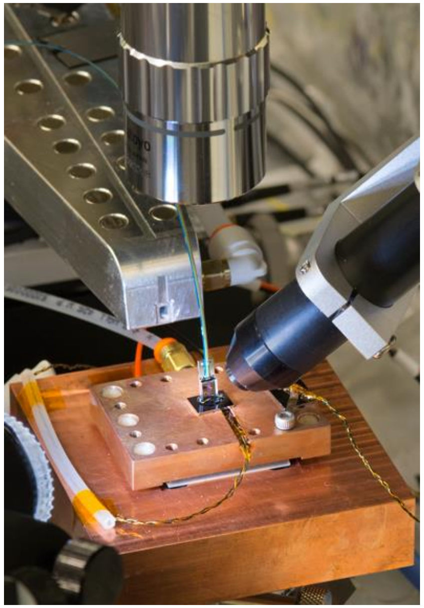
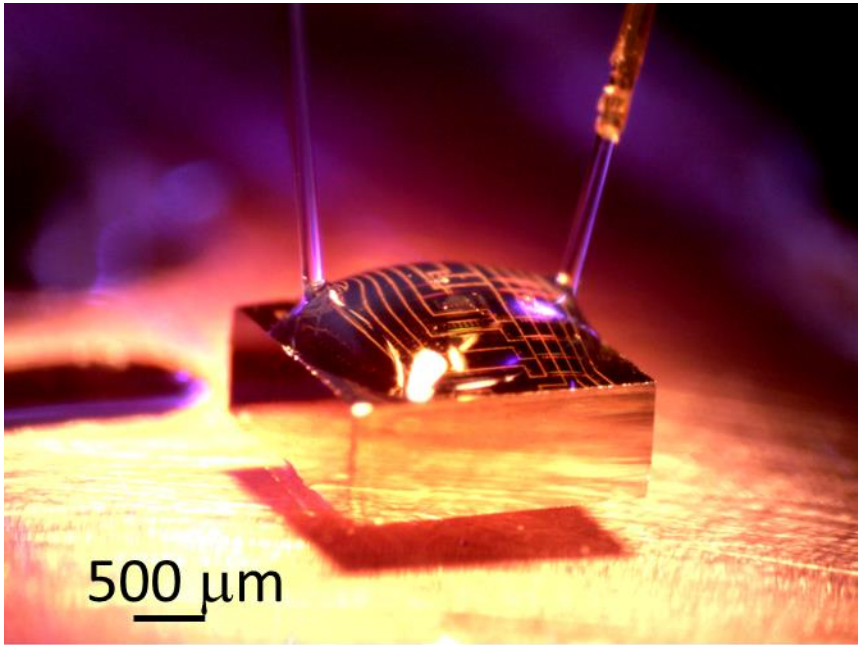
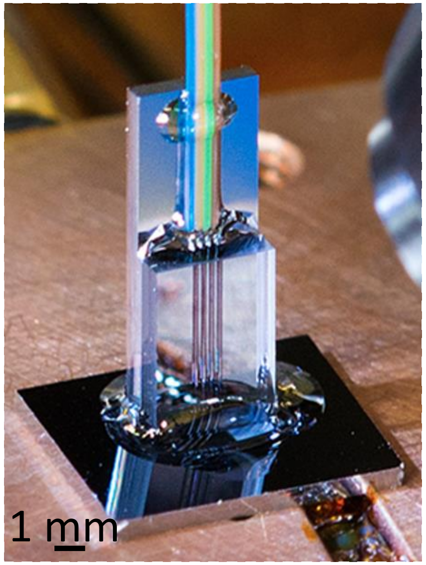


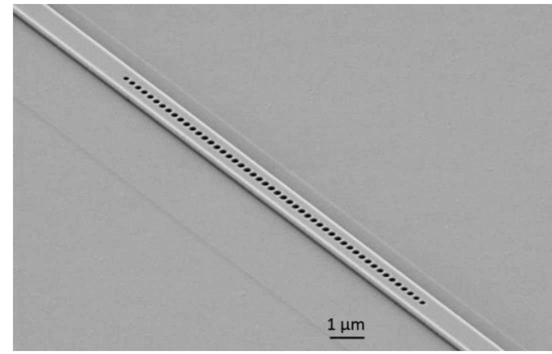


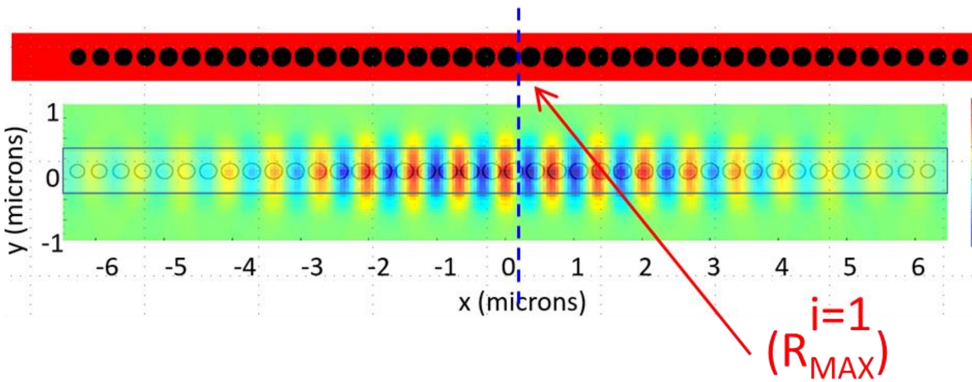


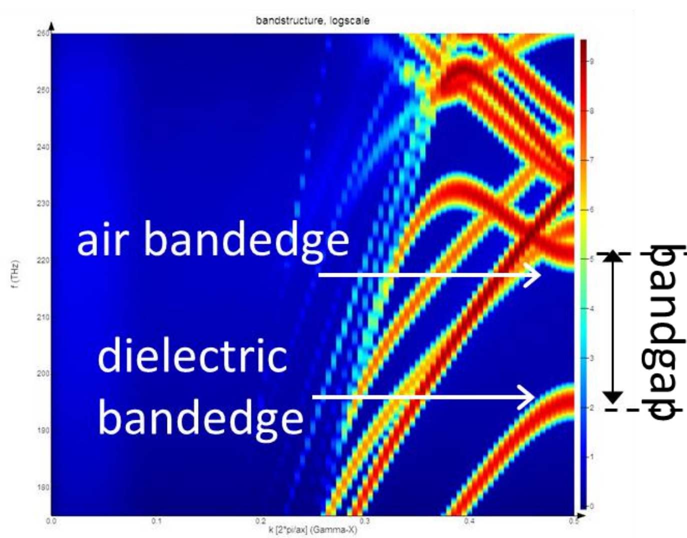
PHYSICAL MEASUREMENT LABORATORY

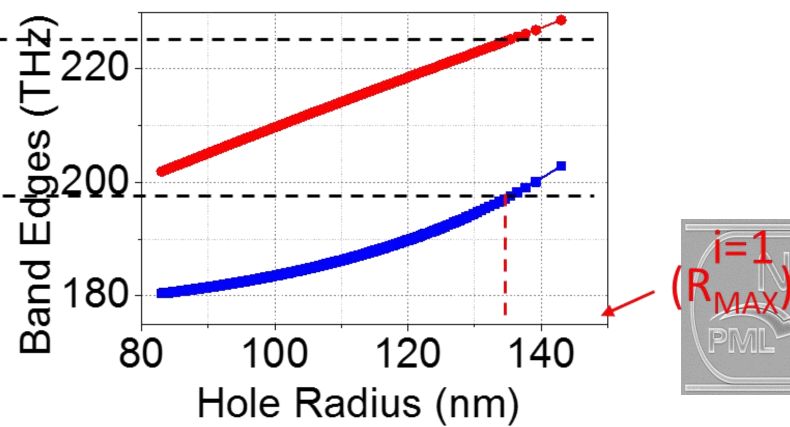
Si Photonic crystal cavity thermometer

In addition to ring resonator and Bragg filter based silicon devices we have also developed photonic crystal cavity (PhCC) based temperature sensors. Using theoretical calculations we can deterministically design the device characteristics.



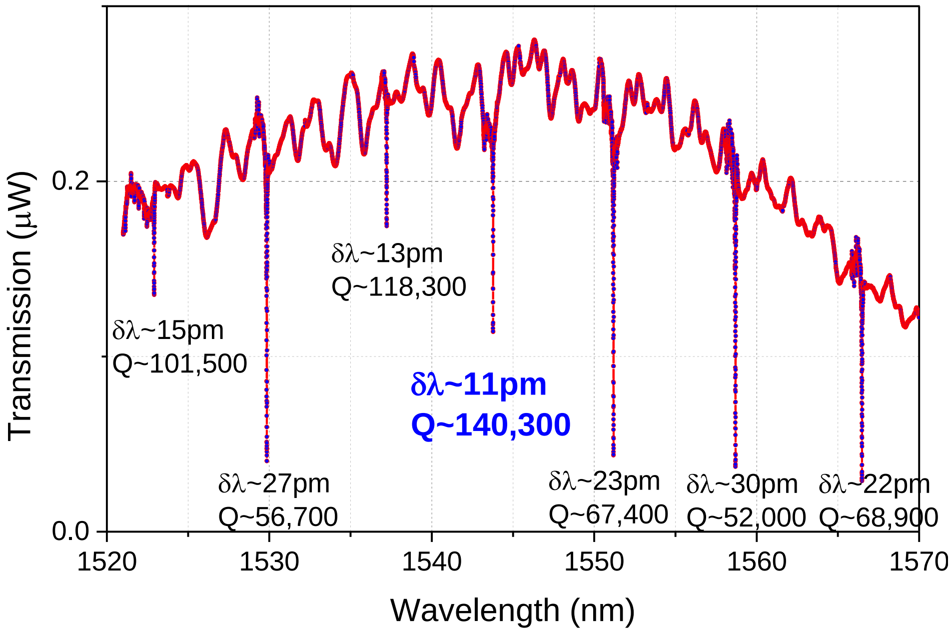




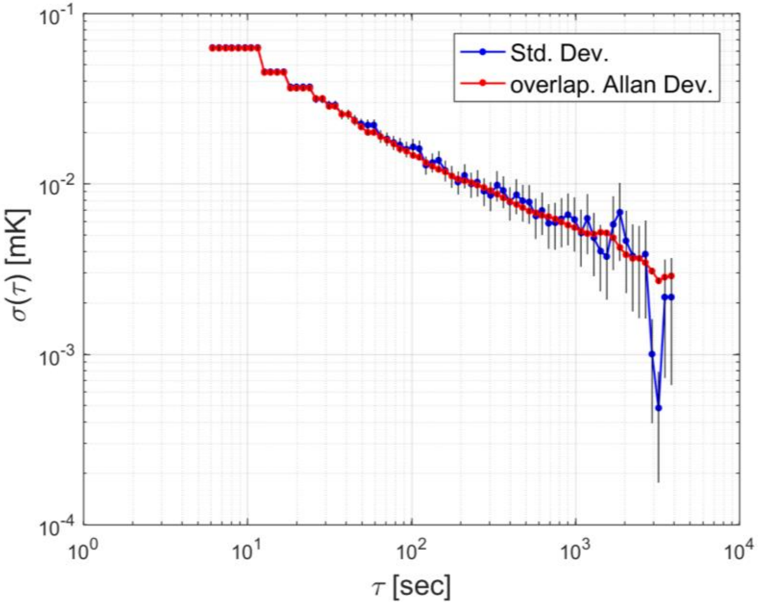


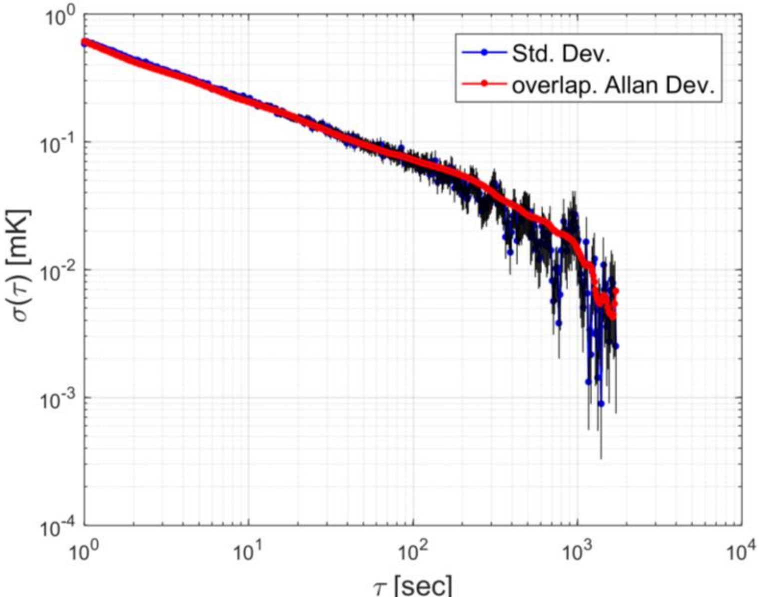
Photonic Thermometry: Gen III Thermometers Reach Q-factors of 10^6

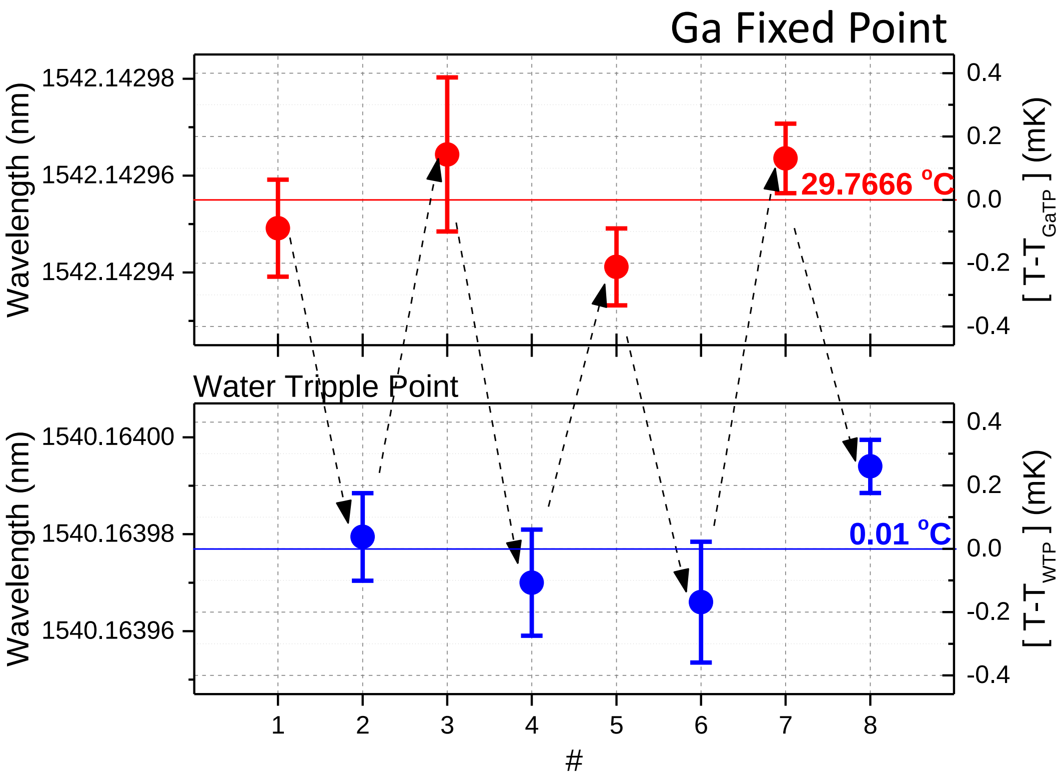
With these new class of devices we now routinely achieve Q's of 100K or more. Improvements in design and materials have reduced hysteresis. These devices are currently being tested in a Triple Point of Water cell.



Si Photonic crystal cavity thermometer in TPW and Ga Cell







Reproducibility/Hysteresis between TP_{WATER} & Ga_cell ≈ **0.18 mK**

Optomechanical Temperature Standard

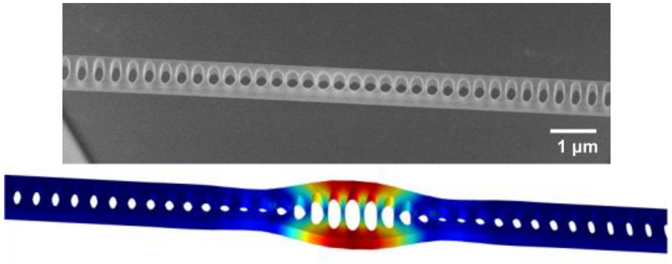
On-chip temperature standard

- Small, portable, optically based device
- Link temperature to fundamental constants
- Easily paired with high-sensitivity silicon photonic thermometer

Optomechanical Implementation

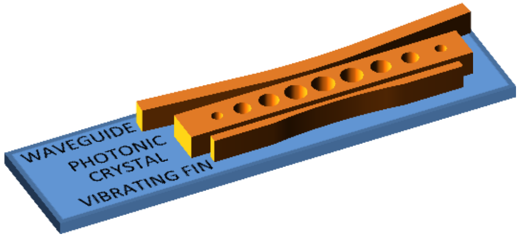
- Optically measure Brownian motion of nanomechanical resonator
- Quantum backaction scale dictated by Heisenberg uncertainty relation
- Measure scale of backaction via correlations between optical force and induced motion
- Noise correlations make temperature scale in units of vibrational quanta, $\hbar\omega_m/k_B$

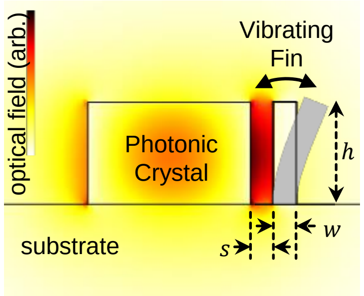
First generation device
Si_3N_4 Optomechanical Crystal



- Proof-of-principle demonstration: T. P. Purdy, K. E. Grutter, K. Srinivasan, J. M. Taylor, *Science* (2017).

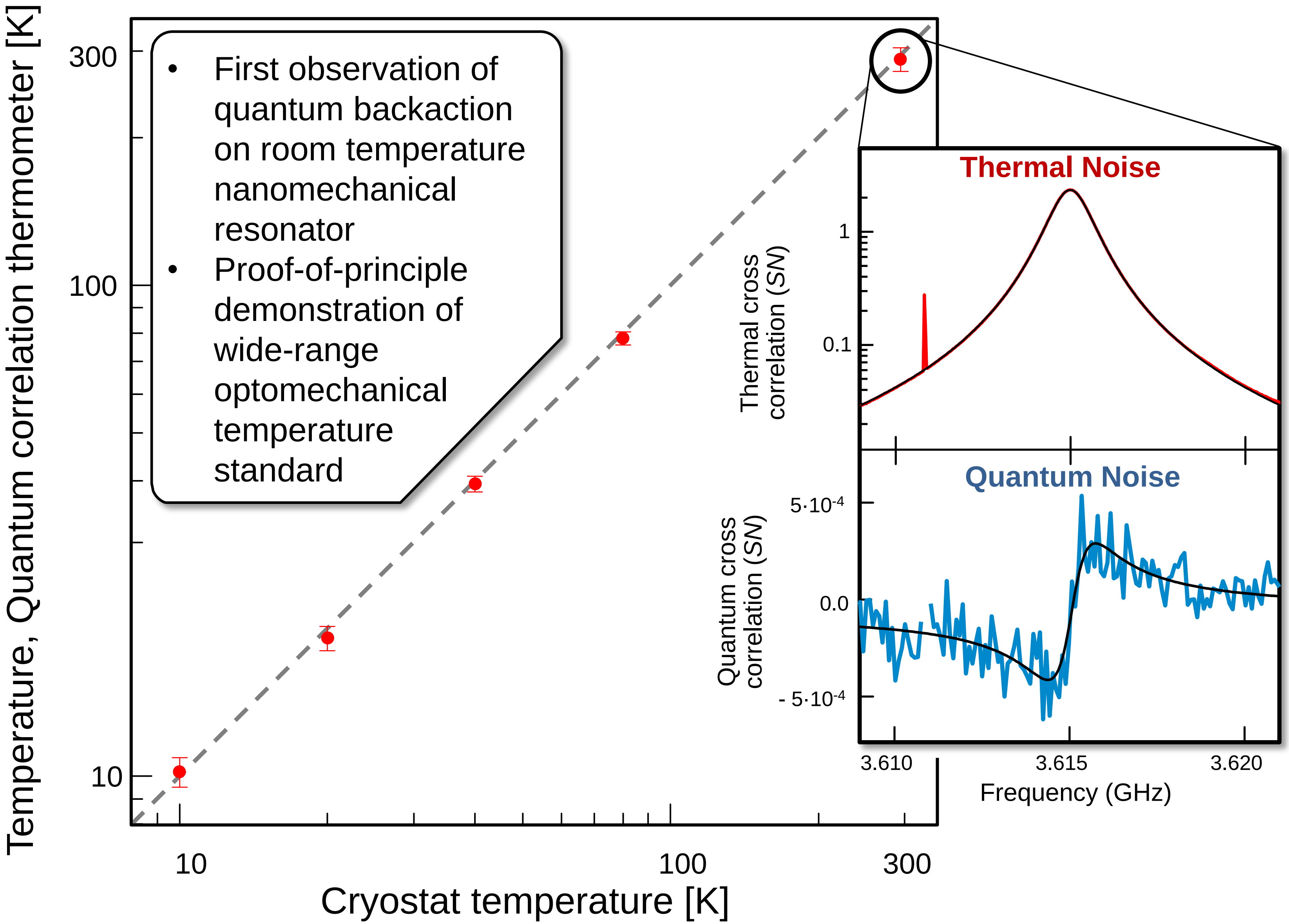
Next generation device
Silicon-on-insulator optomechanical fin





- Simplified and robust fabrication
- Slot-mode optomechanical coupling
- Increased bandwidth and SNR
- Superior heat dissipation
- Easy integration with silicon photonics

Optomechanical Quantum Correlation Thermometry



T. P. Purdy, K. E. Grutter, K. Srinivasan, J. M. Taylor. "Quantum Correlations from a Room Temperature Optomechanical Cavity" *Science*, (2017).

Photonic Thermometry in High Radiation Environment

We have recently demonstrated that SiO_2 passivated Si devices can survive at least 1000 kGy of gamma radiation exposure. Downshift in resonance corresponds to ~300 mK error in temperature at 20 °C

Photonic thermometers can be used in high radiation environments like nuclear power plants, space or dosimetry calibration labs without significant modification to existing technology.