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QPRA: Optical Ring Resonator Strain Sensors for HEP and QIS

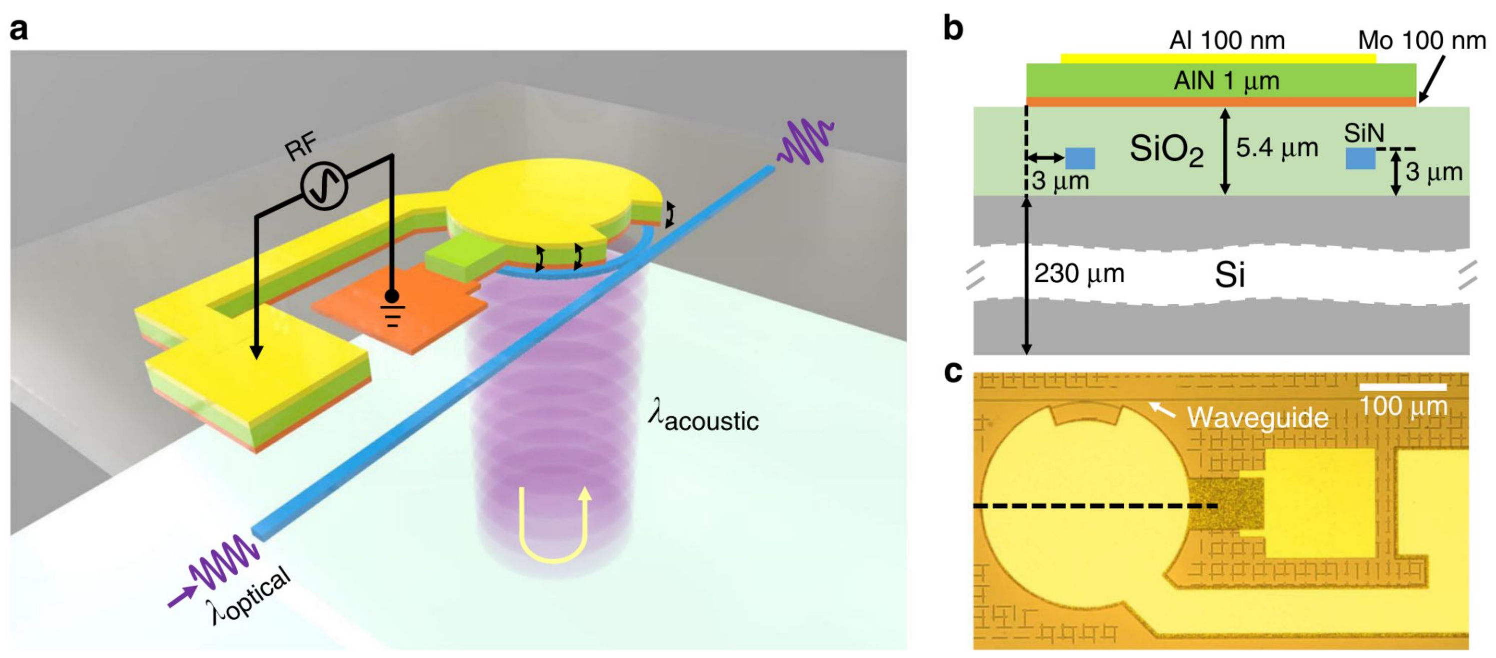
Dylan J Temples, Fermi National Accelerator Laboratory May 7, 2024 QSC All-Hands Meeting

Phonon bursts produced by strain release are a primary driver of the low-energy excess in dark matter (DM) searches and limitation to millisecond coherence times in superconducting qubits [1-4].

Sensors able to directly probe stresses in a detector provide insight into this non-radiogenic background.

This motivates the development of cryogenic, strain-sensitive devices to add to the repertoire of sensors for fundamental physics.

Embedded SiN Optical Strain Sensors



(Left) Rendering of the components of the strain sensor. The embedded waveguide and optical ring resonator are shown in blue, while the RF components comprising the piezo actuator are shown in orange, green, and yellow. (Top right) A cross-section of the device showing the material layers and thicknesses. (Bottom right) An optical microscope image of the device. Images reproduced from [5].

Optical Ring Resonators: Photonic devices developed for microwave-to-optical signal transduction [5] offer potential for rejecting stress-release events.

- ➢ Veto low-energy background events in DM searches
- ➢ Optimize qubit device and packaging design to minimize stress
- ➢ Direct particle detection through phonon channel

Stress-Optical Effect: presence of strain field modulates dielectric constant of resonator → shifts λ_r → change in on-resonance optical transmission.

Co-Investigators: Alaina Attanasio, Daniel Baxter, Sunil Bhave, Daniel Bowring, Bryan Ramson, Jason St. John

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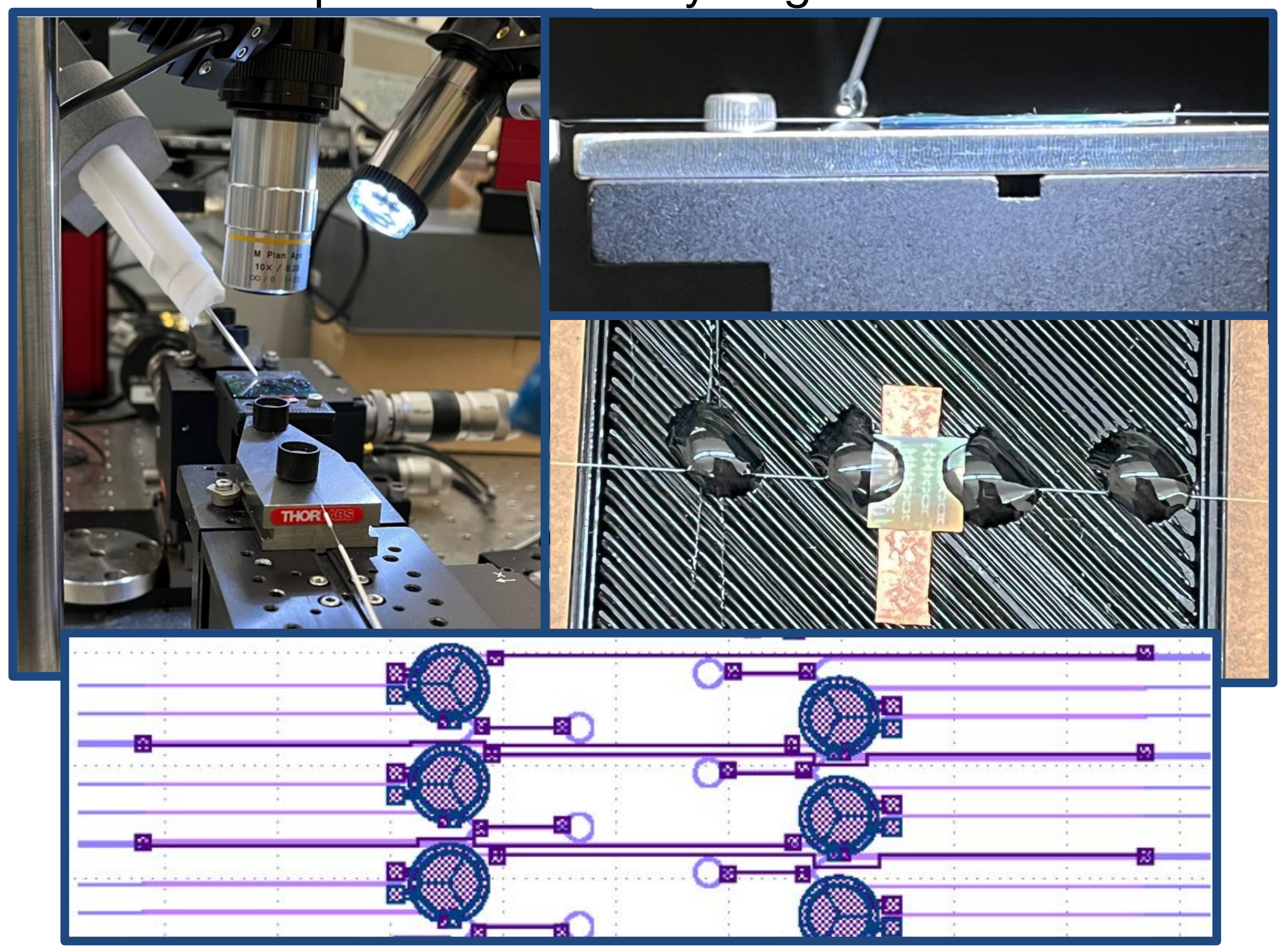
Device Packaging for Cryogenic Use

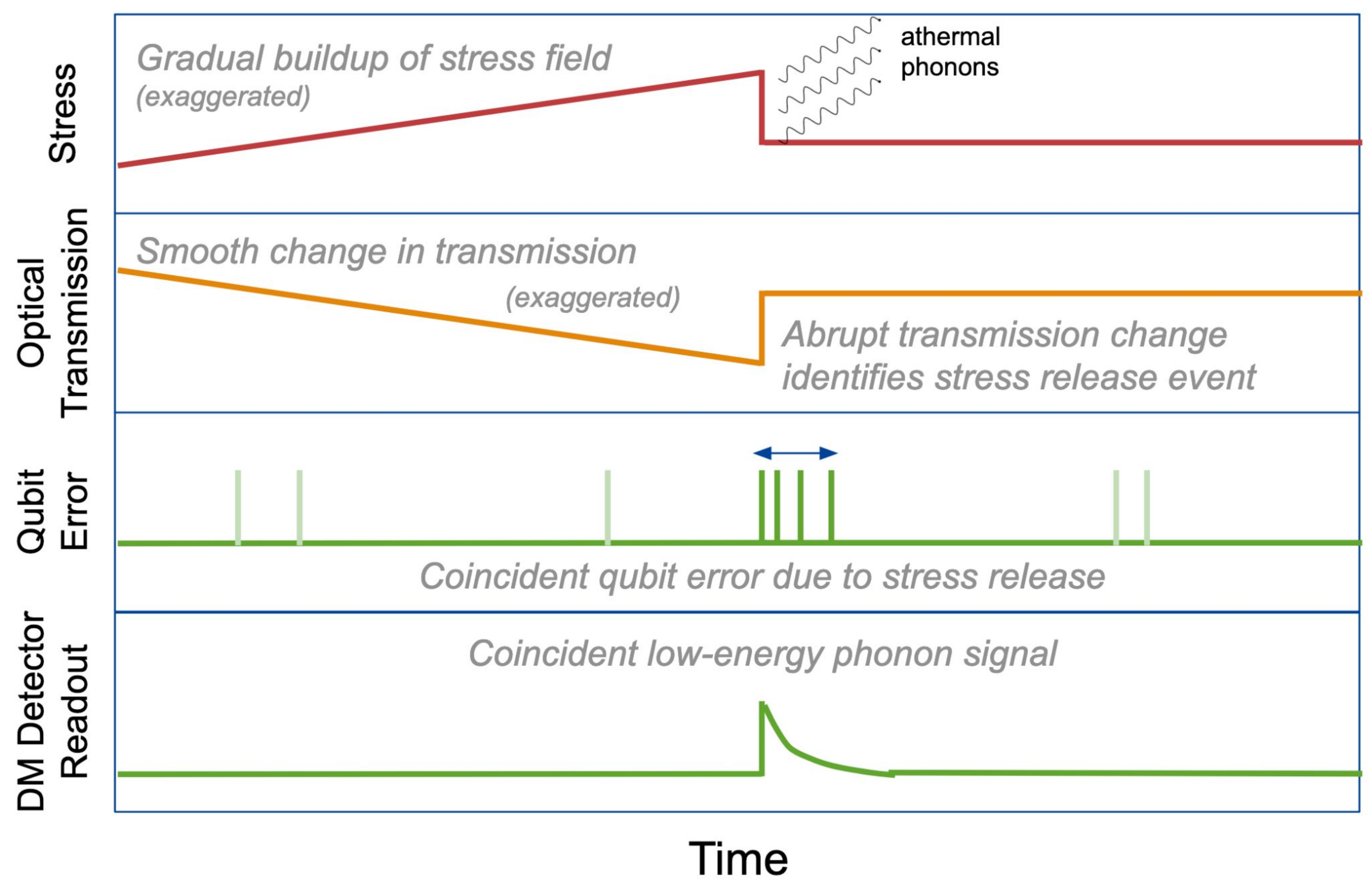
Coupling of the device to optical fibers for readout at cryogenic temperatures requires:

- Precise room-temperature alignment to minimize loss.
- Robust packaging to ensure optical connection survives repeated thermal cycling.



(Top Left) Packaging platform at Purdue University for coupling ORR devices to optical fibers for cryogenic deployment. (Top Right) Profile view of epoxy application for fiber coupling to ORR chip facets. (Middle Right) Example of packaged device on 3D-printed substrate. (Bottom) Section of ORR device design showing 6 resonators and coupled piezoelectric actuators. Images courtesy of A. Attanasio (Purdue).

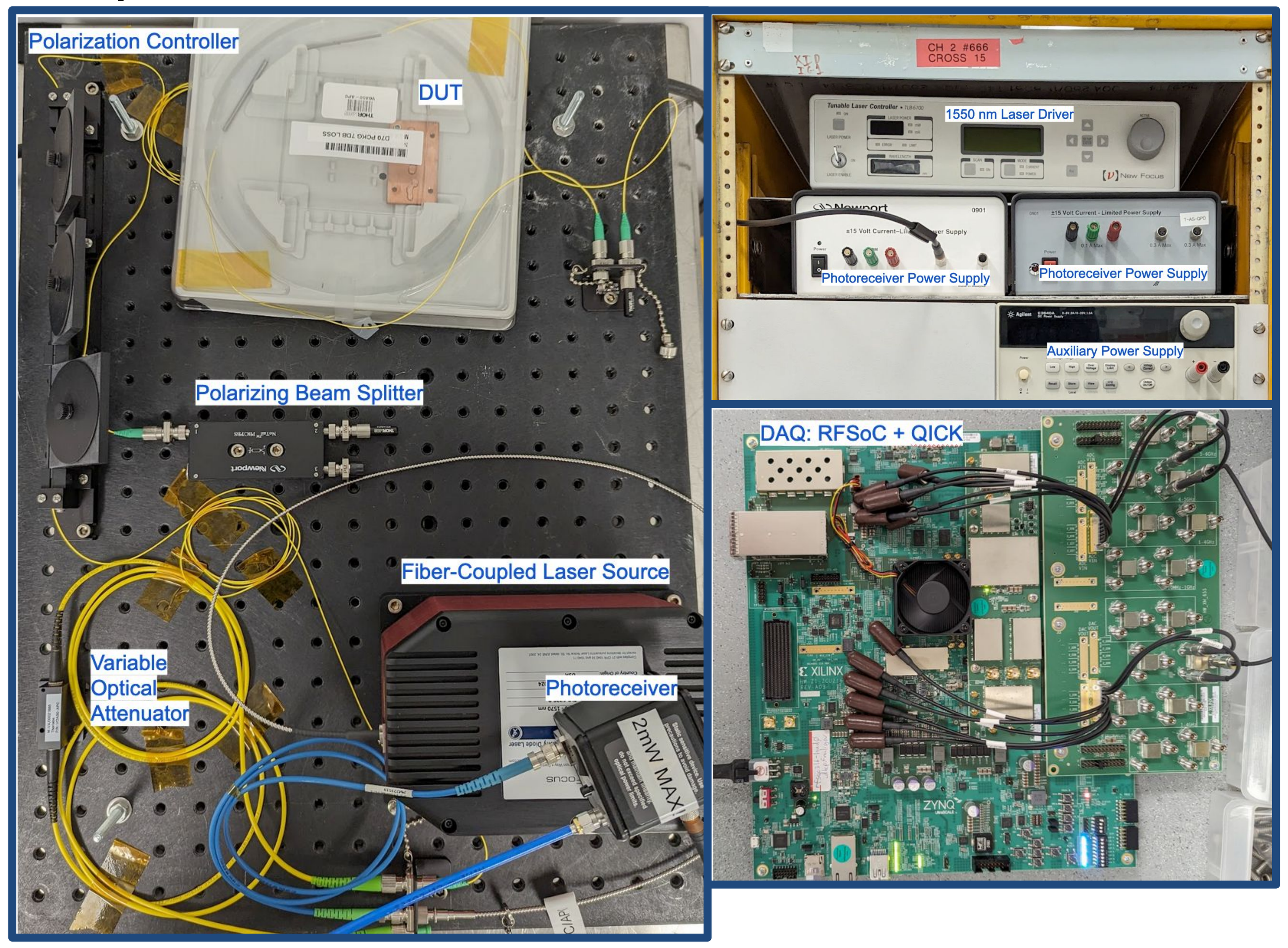
Strain Release Veto



Schematic representation of how a strain sensor might be used to identify strain buildup as the progenitor to decoherence events in superconducting qubit operation or reject a low-energy strain-release event in a DM search. The red trace shows the buildup and release of a strain field due to, e.g., differential contraction of different materials on a device. The orange trace shows the on-resonance transmission change due to the stress-optical effect. The green traces represent measurements of qubit error or the readout of a phonon-sensitive DM detector.

Fermilab Optical Testing Platform

Warm testing of first device underway at FNAL, while preparations are made to install in the QUIET cryogenic facility at Fermilab.



The room-temperature ORR testing platform at Fermilab, used to evaluate device performance before deploying at millikelvin temperatures.

Current Status & Near-Term Results

Goal: Sufficiently characterize the response to radiation (optical and gamma photons) in order to inform ORR design and integration with existing DM detector and superconducting qubit chip architecture.

Current status:

- Warm testing platform set up at Fermilab
- Final stages of equipment procurement
- First packaged device delivered 4/18
- Optical control and DAQ commissioning underway

References:

[1] Adari *et al*. EXCESS workshop: Descriptions of rising low-energy spectra. *SciPost Phys. Proc.* **9**, 001 (2022).

[2] Anthony-Petersen *et al*. A Stress Induced Source of Phonon Bursts and Quasiparticle Poisoning. *arXiv:2208.02790* (2022).

[3] Mannila *et al*. A superconductor free of quasiparticles for seconds. *Nat. Phys.* **18**, 145–148 (2022).

[4] Cardani *et al*. Reducing the impact of radioactivity on quantum circuits in a deep-underground facility. *Nat Commun* **12**, 2733 (2021).

[5] Tian *et al*. Hybrid integrated photonics using bulk acoustic resonators. *Nat Commun* **11**, 3073 (2020).