Transduction for New Regimes in Quantum Sensing

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Quantum transduction is the coherent manipulation of quantum states at the boundaries of quantum systems, and it lies at the heart of engineering these "systems" into networks, sensors or computers. For example, quantum transduction between superconducting or atomic qubits and photons plays a crucial role in implementing quantum gates and preparing entangled states for quantum metrology. Coherent quantum transduction between different modalities is an essential component of many emerging quantum information science (QIS) applications, as it provides an effective way for linking the classical and quantum world, and for transporting quantum information on macroscopic scales. The implementation of many quantum systems requires transduction between microwave and optical wavelengths for computing and networking, and from wavelengths within this range to microwave or optical systems for sensing.

For applications that link microwave qubits with optical networks, transducer performance is determined by the achievable data rates and fidelity in transferring quantum information between these two extreme wavelengths. Unfortunately, the physical processes required for direct transduction between these frequencies are inherently dissipative, limiting qubit performance at millikelvin (mK) temperatures. Rather than direct transduction, we are exploring a two-step transduction scheme utilizing the mm-wave regime as an intermediate step. Microwave to mm-wave transduction will be achieved with a superconducting resonator at mK temperatures before transporting the photon and its quantum information to higher temperatures. Converting to mm-wave frequencies can be achieved with much lower dissipation, and even at these intermediate photon energies coherence can be maintained at elevated temperatures. Low-loss mm-wave photonics could also allow preservation of quantum information at room temperature for a simpler network at laboratory scales. Such a network could enable hybrid quantum information processing leveraging the complementary strengths of superconducting and cold-atom qubits, the latter coupling to mm-waves via transitions between Rydberg states.

In addition to linking different QIS modalities, another motivation for utilizing the mm-wave regime is for dark matter searches. A significant portion of the candidate dark matter spectrum spanning the μeV-eV range lacks techniques for processing or transducing quantum states, thereby limiting the reach of quantum sensors. The frequency range for axions above ~10 GHz (~40 μeV) is beyond the reach of current experiments (ADMX). Development of resonant structures that may couple to the axion field at mm-wave frequencies is actively being pursued by a number of groups. Transduction of interaction photons from mm-wave to either microwave or optical frequencies will permit quantum-limited photon counting with well-developed devices.

The motivation for this effort is derived from recent theoretical developments in coherent transduction.[1] We propose to study the behavior of such devices, understand their limitations, and optimize for efficiency and fidelity. In a parallel effort, we will demonstrate coherent exchange of quantum information between trapped Rydberg-atom qubits and a high-Q mm-wave resonator. This effort will enable detection of single mm-wave photons, as well as preparation of non-classical photonic and atomic states for enhanced quantum sensing. A secondary objective in both the superconducting and atomic platforms is to investigate mm-wave-to-optical transduction, and develop conceptual designs for a device that will enable broad quantum coherent networking for computing and sensing. Successful execution of this project will demonstrate the versatility and utility of transduction in QIS.

Possible Impacts for Dark Matter Search: Development of a coherent quantum transducer would enable new pathways for executing dark matter searches, extending the reach of current approaches by transducing photons from mm-wave frequencies to either the optical or microwave band. Currently, detectors at these frequencies provide far more sensitive readout of electromagnetic fields. Microwave parametric amplifiers can detect fields between 4-10 GHz at the quantum limit, while emerging microwave-frequency single-photon counters[2] promise many orders of magnitude enhancement of the axion detection.[3] Mm-wave transducers could also be used to link quantum systems (*e.g.* cavities) and distant detectors by utilizing mm-wave transmission lines at significantly higher temperatures, and allowing sensors to be located in controlled environments free from disturbances (*e.g.* strong magnetic fields). In the longer term, as quantum error correction techniques develop, mm-wave transducers may become useful in conjunction with repeater networks to realize telescopes and probes well beyond classical limits.[4] Understanding the fundamental materials science of thin-film superconductors at mm-wave frequencies may also lead to novel building blocks for qubits, opening new avenues for sensing and broader impact in QIS. While many implementations are possible, there is an urgent need to develop transducers with unique mm-wave resonators (*e.g.* dielectric cavity[5]) to enable quantum-limited dark matter searches to cover existing gaps in frequency coverage.

Fundamental Science: While providing the possibility of a significant and unique technical advantage, the mm-wave regime remains virtually unexplored for QIS. There are many key scientific questions for the fundamental physics at play in these quantum systems, spanning the function of materials to the theory of quantum coherent transduction. This proposal specifically aims to investigate: (1) What nonlinear processes minimize the noise added during photon transduction? (2) How do thin-film superconductors behave in the mm-wave regime, what are the pathways for decoherence, and what new materials can enhance nonlinear inductance? (3) What is the impact of geometric structure on the fundamental properties of thin-film superconductors? (4) Does the mm-wave frequency range also provide a fundamental advantage increasing the timescale of quantum coherence with superconducting qubits? (5) What is the impact on thermal noise in quantum links at mm-wave frequencies? (6) What approach to mm-wave detection is superior for a specific (*e.g.* axion) signal: up-conversion and detection at optical frequencies, or down- conversion and detection at microwave frequencies? (7) Can we engineer non-classical states of the mm-wave field that are useful for enhanced quantum sensing of dark matter?

HEP Impact Beyond QIS: The scope of this program has a strong synergy with accelerator R&D programs in the development of both mm-wave and superconducting RF technologies. The development of higher fidelity mm-wave fabrication and new component designs for mode converters, couplers, low-loss waveguides, and cavities as part of this program will provide direct overlap with the structure development and components needed for mm-wave accelerators.[6,7] The properties of thin-film superconductors will be characterized covering a large range in temperatures and frequencies with a specific focus on understanding intrinsic material properties, process defects and improving yield. This program has the potential to greatly expand SRF materials characterization[8,9] with data collected over wide frequency and temperatures down to 10s of mK. Developing coating technologies is a critical need for expanding beyond niobium[10] and to new cavity geometries with lower surface fields and provide more efficient operation.[11]

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