Quantum Science and Engineering

Readout of a Transmon Qubit Using a Directional Readout Resonator with Interference Purcell Suppression

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Sponsorship: NSF Graduate Research Fellowship, MIT-IBM Watson AI Lab

Impedance mismatch in the readout bus is a leading cause of high variance in measurement rate κ in superconducting quantum processors. Moreover, the addition of bulky and high-magnetic field circulators and isolators is often needed for impedance matching. In this work, we demonstrate transmission-based readout of a transmon qubit using a directional readout resonator. Whereas a typical readout resonator would have a sharp dip in $|S21|$ on resonance, our directional resonator demonstrates a dip of less than 1dB on resonance, thus closely preserving the 50-ohm readout bus. This both maximizes measurement efficiency and avoids needing a weakly-coupled port, a major source of impedance mismatch in many standard qubit readout schemes. To enable fast readout and reset, we propose a novel interference Purcell filter compatible with directional readout and demonstrate Purcell suppression by 2 orders of magnitude over a bandwidth of more than 600 MHz. This architecture is expected to facilitate more scalable and modular design of quantum processors.

Transferable Optical Enhancement Nanostructures by Gapless Stencil Lithography

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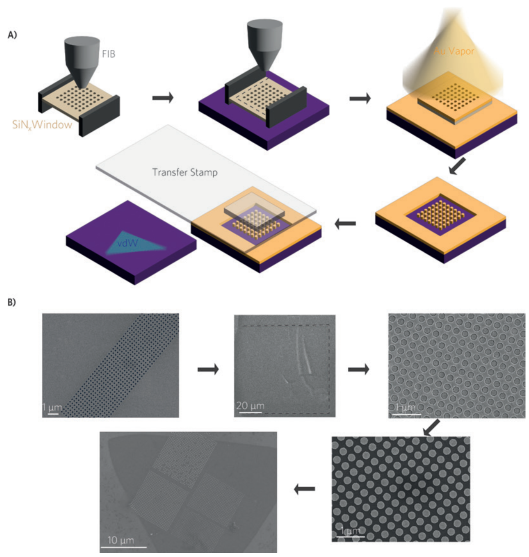
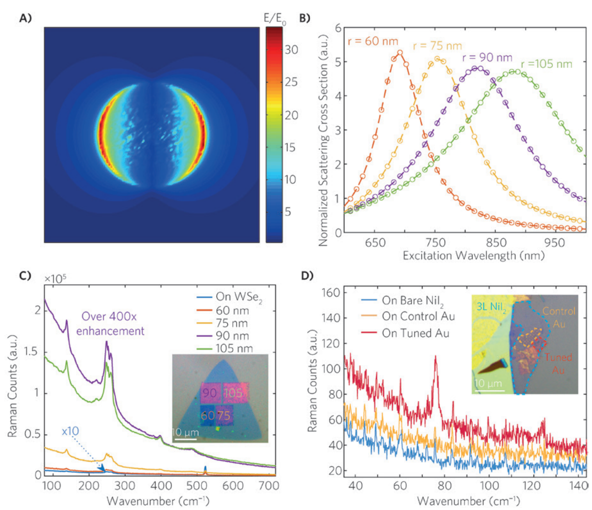
Sponsorship: U.S. Department of Energy, Office of Science National Quantum Information Science Research Center's Co-design Center for Quantum Advantage (C2QA) contract DE-SC0012704, Raith VELION FIB-SEM in the MIT.nano Characterization Facilities (Award: DMR-2117609), MathWorks Science Fellowship (Award: 4000182189)

Optical spectroscopy techniques are central for the characterization of the electronic properties and symmetry of two-dimensional (2D) quantum materials. However, the reduced volume of atomically thin, micron-sized samples often results in a cross section that is far too low for conventional optical methods to produce measurable signals. In this work, we developed a scheme based on the stencil lithography technique to fabricate transferable high-resolution optical enhancement nanostructures for Raman and photoluminescence spectroscopy (Figure 1). Equipped with this new nanofabrication technique, we designed and fabricated plasmonic nanostructures to tailor the interaction of few-layer materials with light. We demonstrate an orders-of-magnitude increase in the Raman intensity of ultrathin flakes of 2D semiconductors and magnets (Figure 2) as well as selective Purcell enhancement of quenched excitons in WSe_2/MoS_2 heterostructures. We provide evidence (Figure 2d) that the method is particularly effective for optical studies of air-sensitive materials, as the fabrication and the transfer can be performed in situ. The fabrication technique can be easily generalized to enable a high degree of flexibility for functional photonic devices and surfaces.



▲Figure 1: Fabrication steps with corresponding SEM/FIB images. SiNx membranes are milled, flipped, and lowered to contact the substrate. The window is removed, and the material is evaporated. After the membrane lift-off, the nanostructures can be transferred onto the sample.



▲Figure 2: Raman enhancement due to transferred plasmonic arrays. A, Illustration of electric field enhancement due to a single gold nanodisk. B, Wavelength-dependent normalized scattering cross sections for various radii. C, Raman spectra of WSe_2. D, Raman spectra of three-layer NiI_2.

FURTHER READING

- J. -H. Hsia, J. A. Perozek, and T. Palacios, "First Demonstration of Optically-Controlled Vertical GaN finFET for Power Applications," *IEEE Electron Device Letters*, vol. 45, no. 5, pp. 774-777, May 2024. doi: 10.1109/LED.2024.3375856

High-Temperature Nanowire-Based Superconducting Circuits

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Sponsorship: NSF Engineering Research Center for Quantum Networks, MIT Lincoln Lab SNSPD Array Program

Superconducting electronics are promising for energy-efficient computing beyond CMOS, cryogenic sensor readout, and future quantum computing platforms. Among various families of superconducting circuits, nanowire-based cryotrons have proven to be quite useful in applications, including serving as pre-amplifiers for superconducting nanowire single-photon detector (SNSPD) readout, interfacing JJ-based circuits with CMOS circuits, functioning as digital logic circuits, and superconducting memory cells. These nanowire-based cryotrons are three-terminal devices which are immune to stray magnetic fields and capable of driving high-impedance loads while providing a high fan-out of digital signals. However, their operation has been demonstrated primarily in low-Tc material systems such as NbN, NbTiN, MoN, and WSi, resulting in their operating temperatures usually below 10K. However, in quantum communication and computing, there is a growing need to reduce thermal loads at the 4K or mK stage to accommodate more space for qubits and vacancy centers. This can be achieved by shifting cryogenic logic, memory, and microwave circuits to the 40K stage.

In this work, we investigate the performance of nanocryotrons fabricated on a thin film of YBCO with a critical temperature of 93K. Since the critical temperature of YBCO degrades when exposed to humidity and temperature, fabricating nanowires on YBCO without degrading its superconducting property is quite challenging. Additionally, YBCO does not react to commonly used reactive ion gases employed in etching. We will discuss how to address these challenges in the fabrication process of sub-100 nm width nanowires and present the current-voltage characteristics of the fabricated devices at 40K. Furthermore, we will explore how the device performance changes with increasing operating temperature, and then we will discuss how this work can pave the way for transitioning superconducting nanowire-based devices from sub-4K operation to a more affordable and compact liquid N_2 dewar setup.

Effects of Helium-ion Exposure on Superconducting-nanowire Single Photon Detectors

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Sponsorship: National Science Foundation (NSF) CQN Center

Ultra-fast single-photon detectors can be useful for applications including quantum optical communication systems, high-speed communication, lightweight cryogenics for space crafts and biomedical use. In particular, high-temperature superconductors can allow for the development of superconducting-nanowire single-photon detectors (SNSPDs) that can operate at higher temperatures than standard superconductors, enhancing the efficiency, simplicity of use, viability, and affordability of the device. Unfortunately, the fabrication of high-temperature superconducting nanowires damages the material. Moreover, the realization of large and uniform detector arrays formed by hundreds or thousands of detectors is fraught with complexities. As a result, the opportunity to modify the detector metrics through post-processing is attractive.

In this work, the effects of helium ion irradiation on superconductive nanowires single photon detectors are systematically investigated. We exposed NbN single nanowires and SNSPDs with a total active area of 5 x 5 μm^2, 8 x 8 μm^2, 10 x 10 μm^2 to a range of irradiation doses from ~ 10^{14} to ~ 10^{20} ions/cm^2 and thus demonstrated the impact of different doses on the target materials as well as improved the detector metrics. With an applied dose of $2.6 \cdot 10^{17}$ ions/cm^2, we were able to obtain an increase in the detector count rate of around a factor of 5. These results lead to the possibility of reaching homogeneous detector metrics after fabrication and on the same chip. This capability suggests the potential to achieve uniform and consistent detector performance across an entire chip, offering a solution to the challenge of creating large, high-quality detector arrays.

High Frequency Microwave Packaging for Josephson Traveling Wave Parametric Amplifiers

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Sponsorship: NSF Graduate Research Fellowship, the US DOE Office of Nuclear Physics (DE-FOA-0002110), the US NSF, the PRISMA+ Cluster of Excellence at the University of Mainz

The detection of single-photon microwave signals above 12 GHz is of significant interest for quantum sensing applications in neutrino mass measurement, dark matter searches, and quantum information processing. Below 12 GHz, quantum-limited amplification can be achieved with high-gain, broadband, and low-noise Josephson traveling wave parametric amplifiers (JTWPAs). However, standard microwave packaging for JTWPAs introduce package modes above 12 GHz, as well as impedance mismatches at the connectors and wirebonding locations that hinder the performance of JTWPAs. Here we present an approach to high frequency microwave package design that optimizes package and connector modes, minimizes wirebonds on interposer chips, and employs signal-line compensation strategies for better impedance matching throughout. The package is modular, easily prototyped, and is well-matched up to 27 GHz. This package will be deployed with a K band JTWPA tailored to the Project 8 neutrino mass measurement experiment, which will enable the detection of cyclotron radiation from single electrons with a signal-to-noise ratio improvement of an order of magnitude compared to current HEMT amplifiers. Since this design features low reflection and minimal spurious modes over a broad range of frequencies, this package can also be tailored to suit a wide range of superconducting quantum devices.

A Superconducting Bridge Rectifier Using the Asymmetric Surface Barrier Effect

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Sponsorship: Department of Energy, National Laboratory LAB 21-2491 Microelectronics grant

Superconducting nanowire single-photon detectors (SNSPDs) arrays are currently being explored for quantum communication, bio-imaging, and space exploration. To enhance the scalability of such arrays based on niobium nitride (NbN) thin films, on-chip integration of nanowire-based control electronics is essential. In particular, a superconducting diode can be helpful for signal rectification and biasing. The superconducting diode effect (SDE) has been demonstrated with several technologies but integrating them into NbN-based systems can be challenging due to platform incompatibility. The asymmetric Bean-Livingston surface barrier effect in thin-film micro-bridges under external magnetic fields provides a potential solution. The effect has been observed in NbN wires with limited reproducibility. Moreover, half-wave rectification at more than 100 kHz and multi-diode circuits have never been shown. Overcoming these limitations would make it easier to construct more complex structures, like an AC-to-DC converter. The latter can assist in lowering the number of cables exiting the cryostat by frequency multiplexing the bias levels of several superconducting devices on chip.

We fabricated superconducting diodes by creating a lithographic triangular defect on one side of 1-μm wide NbN micro-bridges. By applying a 4-mT magnetic field, we observed the SDE with a 42% rectification efficiency at 4.2 K. We used these devices to demonstrate a bridge rectifier for full-wave rectification of 3-MHz sinusoidal signals, and AC-to-DC current conversion at 50 MHz, with an estimated 50% power efficiency. Additionally, we simulated a bias distribution network for SNSPDs with frequency-multiplexed bias levels by exploiting AC-to-DC converters based on the superconducting bridge rectifier. This proof-of-concept work demonstrates the possibility of designing complex circuits with superconducting diodes, paving the way for the scalability of SNSPD arrays and other superconducting systems.

FPGAs for Electrical Characterization of Superconducting Nanowire Based Circuits

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Sponsorship: DOE FNAL Microelectronics, DoD NDSEG Fellowship, Alan L McWhorter Fund Fellowship

Superconducting nanowire-based computing devices have the potential to play a crucial role in environments that demand extreme power efficiency, radiation hardness, and resilience to magnetic fields. Memory is a critical component of any computing system; thus, the current lack of scalable high-performance superconducting memory is a critical challenge to overcome. Superconducting Nanowire Memory (nMem) technology is a promising solution to this problem.

Current efforts to improve nMem designs and operation rely on expensive arbitrary waveform generators (AWGs) and oscilloscopes that are not well suited for parallelized memory cell tests or quickly providing high resolution analyses. Testing often involves large parameter space searches that take hours. Furthermore, the low memory capacity of the AWG greatly limits the resolution of our search space. Here, the AWG acts as the principal bottleneck.

An FPGA provides the necessary performance to increase parallelism without a proportional increase in cost, greatly improving testing resolution and speed and reducing test time from hours to seconds. In this project, we have developed a custom analog frontend to interface the FPGA with superconducting nanowires. Importantly, the flexibility of this system allows for a generalized application to any electronic system that demands a specialized testing procedure involving arbitrary signal processing and generation. The money, time, and energy that this innovation will save on validating cryogenic electronics in general will significantly improve our progress in developing these technologies.

Superconducting Nanocryotrons for Single-photon Detector Readout

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Sponsorship: Department of Energy Fermi National Accelerator Laboratory Microelectronics (DE-AC02-07CH11359), MIT Vanu Bose Presidential Fellowship, NSF Graduate Research Fellowship (2141064), Department of Defense National Defense Science and Engineering Graduate Fellowship.

Efficient, low-noise single-photon detection is crucial to sensing, communication, and computing applications. To date, superconducting nanowire single-photon detectors (SNSPDs) are the most efficient such detectors, with the lowest dark count rates and shortest timing jitter in the ultraviolet to infrared (IR) wavelengths.

Many applications require detection in the mid-IR. However, the read-out signal from SNSPDs produced for these wavelengths is usually weaker than for ultraviolet and visible detectors. Consequently, detection at longer wavelengths necessitates a low-noise, low-energy cryogenic amplifier. High-electron-mobility transistors and cryogenic complementary metal-oxide semiconductor amplifiers can provide amplification, yet they are not scalable due to substantial power dissipation and a lack of integrability with SNSPDs. In contrast, superconducting nanocryotron (nTron) devices provide gain with minimal power dissipation and are easily integrated on-chip with SNSPDs, making them ideal candidates for these purposes.

To optimally amplify SNSPD pulses, nTron devices must provide consistent and maximal gain. Due to heterogeneous current density across nTrons, the location of the nTron choke is a salient design parameter for determining the device's gain. Thus, to ascertain the best choice of choke offset position we have fabricated a wafer with 350 nTron devices and measured their switching characteristics. We are currently working to determine the gain of each device as a function of the location of the choke to develop a model for the optimal nTron design for SNSPD read-out. This design will then improve the performance of SNSPDs in mid-IR and array applications.

Superconductivity and Strong Interactions in a Tunable Moiré Quasicrystal

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Sponsorship: MIT Pappalardo Fellowships, Israel CHE Outstanding Postdoctoral Fellowship in Quantum Science and Technology, Army Research Office MURI, NSF, STC Center for Integrated Quantum Materials, Gordon and Betty Moore Foundation's EPiQS Initiative.
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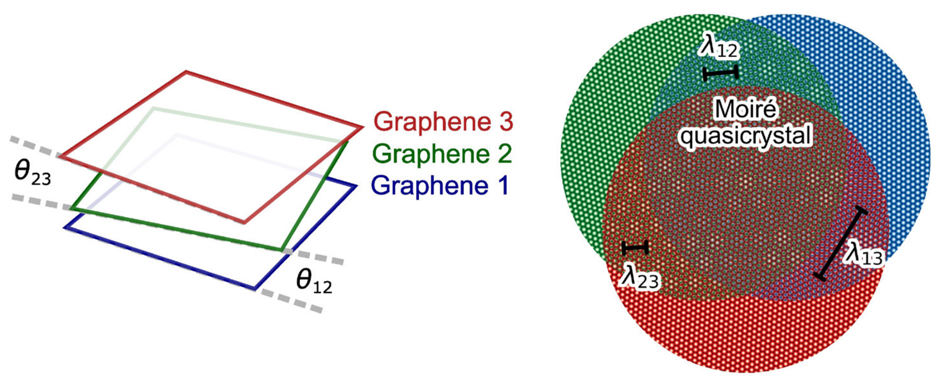
Electronic states in quasicrystals generally preclude a Bloch description, rendering them fascinating and enigmatic. Owing to their complexity and scarcity, quasicrystals are underexplored relative to periodic and amorphous structures. Here, we introduce a new type of highly tunable quasicrystal easily assembled from periodic components. By twisting three layers of graphene with two different twist angles, we form two mutually incommensurate moiré patterns. In contrast to that in many common atomic-scale quasicrystals, the quasiperiodicity in our system is defined on moiré length scales of several nanometres. This "moiré quasicrystal" allows us to tune the chemical potential and thus the electronic system between a periodic-like regime at low energies and a strongly quasiperiodic regime at higher energies, the latter hosting a large density of weakly dispersing states. Notably, in the quasiperiodic regime, we observe superconductivity near a flavor-symmetry-breaking phase transition, the latter indicative of the important role that electronic interactions play in that regime. The prevalence of interacting phenomena in future systems with in-situ tunability is not only useful for the study of quasiperiodic systems but may also provide insights into electronic ordering in related periodic moiré crystals. We anticipate that extending this platform to engineer quasicrystals by varying the number of layers and twist angles and by using different two-dimensional components will lead to a new family of quantum materials to investigate the properties of strongly interacting quasicrystals.



▲Figure 1: Left, three layers of graphene stacked with two different twist angles. Right, every pair of layers (1-2, 2-3, and 1-3) forms an interference moiré pattern with a unique wavelength **λ**. For given twist angles, the different wavelengths are in general incommensurate, forming a novel "moiré quasicrystal."

FURTHER READING

- A. Uri, S. C. de la Barrera, M. T. Randeria, D. Rodan-Legrain, T. Devakul, P. J. D. Crowley, N. Paul, K. Watanabe, T. Taniguchi, R. Lifshitz, L. Fu, R. C. Ashoori, and P. Jarillo-Herrero, "Superconductivity and Strong Interactions in aTunable Moiré Quasicrystal," *Nature,* vol. 620, pp. 762–767, 2023.

Probing Kinetic Inductance in Thin Niobium Diselenide ($NbSe_2$) through Microwave Measurements

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Sponsorship: MIT RLE, MIT EECS, MIT Lincoln Laboratory, Department of Applied Physics, Harvard University, Research Center for Functional Materials, International Center for Materials Nanoarchitectonics

We developed hybrid superconducting microwave resonators incorporating van der Waals (vdW) superconductors to explore the MW response of superconducting 2D materials in the GHz regime. We first developed a reliable technique to contact thin $NbSe_2$, entirely encapsulated with hexagonal Boron Nitride (hBN), with a coplanar Al resonator. Then we fabricated a hybrid Al-$NbSe_2$ resonator and measured the kinetic inductance of thin $NbSe_2$. We report a kinetic inductance of 5 layers of $NbSe_2$ of 0.3 nH/□. Crystalline 2D superconductors with high kinetic inductance can be used in superconducting quantum devices, photon detection, and other quantum sensors.

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