Quantum Instrumentation Control Kit – Defect Arbitrary Waveform Generator (QICK-DAWG): A Quantum Sensing Control Framework for Quantum Defects

E. G. Riendeau[1,2¶], L. Basso[2], J. J. Mah[2,3], R. Cong[2,3], M. A. Sadi[2,4], J. Henshaw[2], K. M. Azizur-Rahman[2], A. Jones[2,5], G. Joshi[2], M. P. Lilly[2], and A. M. Mounce[2¶]

1 Haverford College, US **2** Center for Integrated Nanotechnologies (CINT), Sandia National Laboratories, US **3** Brown University, US **4** Purdue University, US **5** Georgia Institute of Technology, US ¶ Corresponding author

DOI: 10.xxxxxx/draft

Software

- Review
- Repository
- Archive

Editor: Sophie Beck

Reviewers:

- @14shreyasp
- @ktahar
- @sidihamady

Submitted: 28 November 2023
Published: unpublished

Summary

The Quantum Instrumentation Control Kit - Defect Arbitrary Waveform Generator (QICK-DAWG), is an open-source software and firmware package for full quantum control and measurement of nitrogen-vacancy (NV) color-centers in diamond and other quantum defects in semiconductor materials for quantum sensing. QICK-DAWG extends the capabilities of the Quantum Instrumentation Control Kit (QICK, an open-source qubit firmware and software package) to quantum defects by implementing controlled laser pulsing and low frequency readout required for defect initialization, control, and measurement using recently available Radio Frequency System-on-Chip (RFSoC) Field Programmable Gate Arrays (FPGA). In addition to user-friendly software and firmware, QICK-DAWG adds documentation that guides users through hardware setup.

Specifically, the QICK-DAWG package consists of FPGA firmware (modified from the original QICK firmware compiled in Vivado), Python software (that extends QICK for specific pulse programs and altered functionality), instructions for installation and hardware modifications, and a demo Jupyter Notebook . QICK-DAWG's measurement programs consist of specific microwave, laser, and readout pulse sequences built in QICK's Python framework for consistency and extensibility. Pulse sequence programs and data analysis scripts are included to collect and characterize photoluminescence (PL) intensity, optically detected magnetic resonance (ODMR) spectra, PL readout windows, Rabi oscillations, Ramsey interference spectra, Hahn echo spin-spin relaxation times T2, and spin-lattice relaxation times T1. Additional pulse sequence programs and data analysis scripts will be added in the future. QICK-DAWG also implements live-update of plots for PL intensities to optimize laser alignment, broadband ODMR spectra for magnetic field alignment, and Rabi oscillations to optimize microwave antenna alignment or positioning. A setup Readme.md file walks users through rudimentary hardware setup, installation, and modification required for low frequency data collection using RealDigital's RFSoC4x2. The package also has a batch file with directions for easy installation setup for the RFSoC Linux kernel that drives firmware, controls, and reads from the FPGA for offline installation of packages. The demo Jupyter Notebook walks users through typical experimental flow and the configuration of each pulse sequence. Each measurement program includes a method that checks whether all required configurations for pulsing programs are present and a method which provides a visual representation of the plot sequence. Ultimately, QICK-DAWG is an extensible firmware and software package for quantum sensing using NV

The Journal of Open Source Software

color-centers in diamond and other quantum defects using one control hub for consistency among different experimental setups or laboratories.

Related Work

Recent open-source software and commercially available RFSoC FPGA evaluation boards provide a strong foundation for developing an open-source control measurement, software, and firmware package for NVs and other diamond quantum defects. Open-source software packages for quantum control and data acquisition such as ARTIQ (Bourdeauducq et al., 2016), Qubic (Xu et al., 2022), and QICK (Stefanazzi et al., 2022) have been continually developed over the past decade for a variety of quantum experiments. These packages have been developed in response to the shortcoming in both in-house and existing commercial based quantum control systems. Focusing on hardware, recently available RFSoC FPGAs including Xilinx's ZCU216, Xilinx's ZCU111 and Real Digital's RFSoC4x2 can generate control pulses at high frequencies (6–10GHz) and digitize signals from photodiodes and single photon detector modules at high sample rates. The precise high-frequency pulse generation, readout capability, compact size, and relatively low cost of these RFSoC FPGAs make them ideal candidates for defect control hardware.

QICK provides firmware, a high-level Python user interface, and accessible inexpensive hardware making it an ideal platform for extension. Both QICK and Qubic utilize RFSoC FPGAs, however only QICK provides firmware for Real Digital's RFSoC4x2, the lowest cost commercial off the shelf FPGA board. QICK also provides a high-level Python user interface that supports rapid implementation and simple in lab parameter modification . Additionally, QICK is already a popular software package; QICK has been applied to superconducting, spin, atomic, molecular, and optical qubit systems, and has reached 40 labs in the last two years (Shammah et al., 2023). Simple modification to QICK firmware, hardware and software is necessary for implementation of QICK in spin-based quantum control experiments like NVs and other diamond quantum defects. QICK-DAWG implements these modifications, extending QICK.

Statement of need

Open quantum hardware (OQH) is a broad category that covers the open-source tools and components needed to build and control quantum computers, technologies, and sensors. OQH has the potential to accelerate quantum research, quantum technology development, and increase accessibility of quantum computing and quantum sensing. The specific area of OQH that QICK-DAWG fills is open-source instrumentation, control, and data acquisition software.

Currently, quantum sensing with quantum defects is accomplished by research groups assembling their own hardware consisting of many different instruments and creating their own software to control them (Bucher et al., 2019). Timing between instruments, such as microwave generators and switches, arbitrary waveform generators, digital to analog converters, and/or photon counters, is typically provided by a fast FPGA TTL generator triggering independent instruments which can lead to timing offsets that must be accounted for. Thus, there is a lack of consistency in hardware and software for quantum defect-based quantum sensing, a niche that QICK-DAWG fills, in addition to simplified operation as all functionality happens on a single instrument's timing.

QICK-DAWG increases accessibility to NV and defect research through its open-source nature, reduced hardware cost, high-level Python-based user interface, and extensive documentation. In the included documentation and demo, the QICK-DAWG package utilizes the Real Digital RFSoC4x2 as this particular SoC has a relatively low cost. Thus, QICK-DAWG lowers the cost of entry for quantum sensing with RFSoCs by as much as an order of magnitude. QICK-DAWG implementation requires some rudimentary hardware modification and additional hardware that is detailed in the installation Readme document. Thus, QICK-DAWG supports full quantum control and data acquisition of NV centers and other diamond quantum defects—a spin-based open-source software niche not yet filled. Furthermore, through reduced equipment costs, high-level Python user interface, and extensive documentation, QICK-DAWG makes NV quantum measurements accessible to academic and small labs and does not require extensive background knowledge in quantum control hardware.

Current Implementation

At Sandia National Laboratories, we are currently using QICK-DAWG to characterize ensembles of both NVs in diamond and boron-vacancy defects in hexagonal boron nitride. These quantum defects are characterized for PL intensity, T*2, T2, and T1. We characterize both the intrinsic properties of these quantum defects and dependent properties which change in the presence of other materials of interest, i.e., in a quantum sensing experiment. These methods allow us to understand the spin properties of low dimensional materials which cannot be accessed by traditional spin probes [Henshaw et al. (2023)](Henshaw et al., 2022)[Casola et al. (2018)](Wang et al., 2022).

Acknowledgements

We thank S. Uemura and S. Sussman for helping to modify QICK firmware and guidance on using QICK. We would also like to acknowledge J. Feder, J. Heremans, C. Yao, E. Henriksen, F. Balakirev, and J. Kitzman for inspirational and technical discussions.

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia (NTESS), LLC, a wholly owned subsidiary of Honeywell International, Inc., for the DOE's National Nuclear Security Administration under contract DE-NA0003525. This work was funded, in part, by the Laboratory Directed Research and Development Program and performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

This work was supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internships Program (SULI). This work was performed, in part, at the Center for Integrated Nanotechnologies (CINT), an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science.

References

Bourdeauducq, S., Jördens, R., Zotov, P., Britton, J., Slichter, D., Leibrandt, D., Allcock, D., Hankin, A., Kermarrec, F., Sionneau, Y., & others. (2016). *ARTIQ 1.0 (1.0)*. Zenodo. https://zenodo.org/records/51303

Bucher, D. B., Aude Craik, D. P., Backlund, M. P., Turner, M. J., Ben Dor, O., Glenn, D. R., & Walsworth, R. L. (2019). Quantum diamond spectrometer for nanoscale NMR and ESR spectroscopy. *Nature Protocols*, *14*(9), 2707–2747. https://doi.org/10.5281/zenodo.1478113

Casola, F., Van Der Sar, T., & Yacoby, A. (2018). Probing condensed matter physics with magnetometry based on nitrogen-vacancy centres in diamond. *Nature Reviews Materials*, *3*(1), 1–13. https://doi.org/10.1038/natrevmats.2017.88

Henshaw, J., Kehayias, P., Basso, L., Jaris, M., Cong, R., Titze, M., Lu, T. M., Lilly, M. P., & Mounce, A. M. (2023). Mitigation of nitrogen vacancy photoluminescence quenching from material integration for quantum sensing. *Materials for Quantum Technology*, *3*(3), 035001. https://doi.org/10.1088/2633-4356/ace095

Henshaw, J., Kehayias, P., Saleh Ziabari, M., Titze, M., Morissette, E., Watanabe, K., Taniguchi, T., Li, J., Acosta, V. M., Bielejec, E. S., & others. (2022). Nanoscale solid-state nuclear quadrupole resonance spectroscopy using depth-optimized nitrogen-vacancy ensembles in diamond. *Applied Physics Letters*, *120*(17). https://doi.org/10.1063/5.0083774

Shammah, N., Roy, A. S., Almudever, C. G., Bourdeauducq, S., Butko, A., Cancelo, G., Clark, S. M., Heinsoo, J., Henriet, L., Huang, G., & others. (2023). Open hardware in quantum technology. *arXiv Preprint arXiv:2309.17233*. https://doi.org/10.48550/arXiv.2309.17233

Stefanazzi, L., Treptow, K., Wilcer, N., Stoughton, C., Bradford, C., Uemura, S., Zorzetti, S., Montella, S., Cancelo, G., Sussman, S., Houck, A., Saxena, S., Arnaldi, H., Agrawal, A., Zhang, H., Ding, C., & Schuster, D. I. (2022). The QICK (Quantum Instrumentation Control Kit): Readout and control for qubits and detectors. *Review of Scientific Instruments*, *93*(4), 044709. https://doi.org/10.1063/5.0076249

Wang, H., Zhang, S., McLaughlin, N. J., Flebus, B., Huang, M., Xiao, Y., Liu, C., Wu, M., Fullerton, E. E., Tserkovnyak, Y., & others. (2022). Noninvasive measurements of spin transport properties of an antiferromagnetic insulator. *Science Advances*, *8*(1), eabg8562. https://doi.org/10.1126/sciadv.abg8562

Xu, Y., Huang, G., Balewski, J., Morvan, A., Nowrouzi, K., Santiago, D. I., Naik, R. K., Mitchell, B., & Siddiqi, I. (2022). Automatic qubit characterization and gate optimization with QubiC. *ACM Transactions on Quantum Computing*, *4*(1). https://doi.org/10.1145/3529397