Office of the Under Secretary of Defense for Research and Engineering
Deputy Chief Technology Officer for Science & Technology
DCTO(S&T) – Quantum Science Topics
23.2 Small Business Innovation Research (SBIR)
Proposal Submission Instructions

INTRODUCTION

The Office of the Under Secretary of Defense, Research and Engineering (OUSD(R&E) Deputy Chief Technology Officer (DCTO) for Science and Technology (S&T) Office in partnership with the DCTO(S&T) Quantum Science Office seeks to advance scientific discoveries in alignment with the USD(R&E) Quantum Science Roadmap and provide a mechanism to further scientific development, maturation, and commercialization of quantum science technologies. The DCTO(S&T) SBIR program aims to stimulate technological innovation, strengthen the role of small business in meeting DoD research and development needs, foster and encourage participation by minority and disadvantaged persons in technological innovation, and increase the commercial application of DoD-supported research or research and development results. **The DCTO(S&T) SBIR program solicits approaches that combine high-risk with potential for high-reward to address scientific challenges described in the topics below.**

Proposers responding to a topic in this BAA must follow all general instructions provided in the Department of Defense (DoD) SBIR Program BAA.

Proposers are encouraged to thoroughly review the DoD Program BAA and register for the DSIP Listserv to remain apprised of important programmatic and contractual changes.

- The DoD Program BAA is located at: https://www.defensesbirsttr.mil/SBIR-STTR/Opportunities/#announcements. Be sure to select the tab for the appropriate BAA cycle.
- Register for the DSIP Listserv at: https://www.dodsbirsttr.mil/submissions/login.

DCTO(S&T) specific requirements in addition to or deviating from the DoD Program BAA are provided in the instructions below.

Specific questions pertaining to the administration of the OUSD(R&E) DCTO(S&T) Quantum Science Office SBIR Program and these proposal preparation instructions should be directed to: Dr. Karl Dahlhauser, karl.j.dahlhauser.civ@mail.mil.

PHASE I PROPOSAL GUIDELINES

The Defense SBIR/STTR Innovation Portal (DSIP) is the official portal for DoD SBIR/STTR proposal submission. Proposers are required to submit proposals via DSIP; proposals submitted by any other means will be disregarded. Detailed instructions regarding registration and proposal submission via DSIP are provided in the DoD SBIR Program BAA.

Technical Volume (Volume 2)

The technical volume is not to exceed 15 pages of Times New Roman size 11 font and must follow the formatting requirements provided in the DoD SBIR Program BAA. Any pages in the technical volume over 15 pages will not be considered in proposal evaluations.

Cost Volume (Volume 3)

Cost and duration limits will be outlined in each topic. Costs must be clearly identified on the Proposal Cover Sheet (Volume 1) and in Volume 3.

Please review the updated Percentage of Work (POW) calculation details included in section 5.3 of the DoD Program BAA. OUSD(R&E) DCTO(S&T) Quantum Science Office will occasionally accept deviations from the POW requirements with written approval from the Funding Agreement officer.

Company Commercialization Report (CCR) (Volume 4)
Completion of the CCR as Volume 4 of the proposal submission in DSIP is required. Please refer to the DoD SBIR Program BAA for full details on this requirement. Information contained in the CCR will be considered by the OUSD(R&E) DCTO(S&T) Quantum Science Office during proposal evaluations.

Supporting Documents (Volume 5)
In addition to those required in the DoD Program BAA, supporting documents will be accepted/required as indicated in each topic.

PHASE II PROPOSAL GUIDELINES

Phase II proposals may only be submitted by Phase I awardees. Phase II duration and cost limits will be outlined in each topic.

DIRECT TO PHASE II (DP2) PROPOSAL GUIDELINES

15 U.S.C. §638 (cc), as amended by NDAA FY2012, Sec. 5106, and further amended by NDAA FY2019, Sec. 854, PILOT TO ALLOW PHASE FLEXIBILITY, allows DoD to make a SBIR Phase II award to a small business concern with respect to a project, without regard to whether the small business concern was provided an award under Phase I of the SBIR program with respect to such project. OUSD(R&E) DCTO(S&T) Quantum Science Office will conduct a "Direct to Phase II" implementation of this authority for select topics under this BAA, as specified in these instructions.

Each eligible topic requires that proposers provide documentation to demonstrate that the feasibility described in the Phase I section of the topic has been met. **Feasibility documentation cannot be based upon or logically extend from any prior or ongoing federally funded SBIR or STTR work.** Work submitted within the feasibility documentation must have been substantially performed by the proposer and/or the PI. If technology in the feasibility documentation is subject to Intellectual Property (IP), the proposer must either own the IP, or must have obtained license rights to such technology prior to proposal submission, to enable it and its subcontractors to legally carry out the proposed work.

If the proposer fails to demonstrate technical merit and feasibility equivalent to the Phase I level as described in the associated topic, the related Phase II proposal will not be accepted or evaluated.

The Defense SBIR/STTR Innovation Portal (DSIP) is the official portal for DoD SBIR/STTR proposal submission. Proposers are required to submit proposals via DSIP. Proposals submitted by any other means will be disregarded. Detailed instructions regarding registration and proposal submission via DSIP are provided in the DoD SBIR/STTR Program BAA.

A complete proposal consists of the following:
Volume 1: Proposal Cover Sheet
Volume 2: Technical Volume
Volume 3: Cost Volume
Volume 4: Company Commercialization Report
Volume 5: Supporting Documents
Volume 6: Fraud, Waste and Abuse Training

Follow the instructions and guidance provided in section 5.3 of the DoD Program BAA for completing these proposal volumes.

Technical Volume (Volume 2)

The technical volume for DP2 proposals consist of two parts:

- **PART ONE: Feasibility Documentation**: Provide documentation to substantiate that the scientific and technical merit and feasibility described in the Phase I section of the topic has been met and describes the potential commercial applications. Documentation should include all relevant information including, but not limited to: technical reports, test data, prototype designs/models, and performance goals/results. **Maximum page length for feasibility documentation is 10 pages**. If you have references, include a reference list or works cited list as the last page of the feasibility documentation. This will count towards the page limit. Work submitted within the feasibility documentation must have been substantially performed by the proposer and/or the PI. If technology in the feasibility documentation is subject to Intellectual Property (IP), the proposer must either own the IP, or must have obtained license rights to such technology prior to proposal submission, to enable it and its subcontractors to legally carry out the proposed work. Documentation of IP ownership or license rights shall be included in the Technical Volume of the proposal. DO NOT INCLUDE marketing material. Marketing material will NOT be evaluated.
- **PART TWO: Technical Proposal:** Content of the Technical Volume should cover the items listed in section 5.3.c. of the DoD SBIR Program BAA. **The maximum page length for the technical proposal is 15 pages.**

Cost Volume (Volume 3)

Cost and duration will be outlined within each topic. Costs for the Base and Option must be separated and clearly identified on the Proposal Cover Sheet (Volume 1) and in Volume 3.

Company Commercialization Report (CCR) (Volume 4)

Completion of the CCR as Volume 4 of the proposal submission in DSIP is required. Please refer to the DoD SBIR/STTR Program BAA for full details on this requirement. Information contained in the CCR will be considered by DCTO(S&T) during proposal evaluations.

Supporting Documents (Volume 5)

In addition to those required in the DoD Program BAA, supporting documents will be accepted/required as indicated in each topic.

DISCRETIONARY TECHNICAL AND BUSINESS ASSISTANCE (TABA)

The OUSD(R&E) DCTO(S&T) Quantum Science Office will not participate in the Technical and Business Assistance.

EVALUATION AND SELECTION

All proposals will be evaluated in accordance with the evaluation criteria listed in the DoD SBIR Program BAA.

Proposing firms will be notified of selection or non-selection status for a Phase I award within 90 days of the closing date of the BAA.

Refer to the DoD SBIR Program BAA for procedures to protest the Announcement.

As further prescribed in FAR 33.106(b), FAR 52.233-3, Protests after Award should be submitted to osd.ncr.ousd-r-e.mbx.SBIR-STTR-Protest@mail.mil.

OSD Quantum Science SBIR 23.2 Topic Index

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OSD232-001 TITLE: Application-Specific Photonic Integrated Circuit (PIC) for a Quantum System

OUSD (R&E) CRITICAL TECHNOLOGY AREA(S): Quantum Science

OBJECTIVE: Develop an application-specific photonic integrated circuit to serve a specific quantum system (e.g. Rydberg sensor, clock transition). The device should integrate into and be demonstrated with an already existing quantum sensor.

DESCRIPTION: Quantum sensors have demonstrated the ability to surpass classical sensors in areas such as clocks [1], Rydberg sensors [2], and magnetometers [3]. Currently, these devices have limited deployment due to factors such as the large SWaP, a lack of environmental robustness, and limited scalability. A major hurdle in overcoming these issues is the size and construction of typical laser systems associated with the quantum sensors. One solution is the development of a photonic integrated circuit (PIC) [4]. These devices have been shown to significantly reduce the size of a laser system through lithographically small structures in materials such as lithium niobate, silicon nitride, or aluminum nitride while being able to be manufactured at scale. Additionally, they offer significant increases in robustness due to factors such as vibrations [5]. The DoD seeks the development of an application specific PIC to serve a specific quantum sensor or clock as well as the integration into said sensor. Because of the plethora of quantum sensors, the call does not specify a sensor or clock, but rather allows the proposer to suggest their own. This is a call for the integration of a quantum sensor with a PIC, not for the development of a quantum sensor. This may include the development of the laser as well as other components on the photonically integrated circuit, such photodiodes, modulators, optical isolators, waveguides/passive structures, etc. A final integration with a quantum sensor and subsequent demonstration will be required.

PHASE I: A successful phase I will outline the device and a demonstration of feasibility. This can be through extensive modeling, with validation of models being preferred. An already constructed quantum sensor should be described with a path towards integration. Phase I Base amount must not exceed $295,000 for a 12-month period of performance.

PHASE II: Phase II is a prototype delivery of the PIC and quantum sensor to the government. The device should demonstrate the integration of the fabricated photonically integrated circuit with the quantum sensor and display a path towards larger quantities of production. Phase II Base amount must not exceed $1,300,000 for a 24-month period of performance and the Option amount must not exceed $650,000 for a 12-month period of performance.

PHASE III DUAL USE APPLICATIONS: This technology can be used for multiple military technologies such as inertial sensors (accelerometers, gyroscopes), gravity gradiometers, magnetometers and atomic clocks and has a dual use for the same applications in the commercial section.

REFERENCES:

1. Ludlow, A. D., Boyd, M. M., Ye, J., Peik, E., and Schmidt P. O., Optical atomic clocks. Rev. Mod. Phys. 87, 637 (2015).
2. Adams, C. S., Pritchard, J. D., Shaffer, J. P., Rydberg atom quantum technologies. J. Phys. B: At. Mol. Opt. Phys. 53 012002 (2020)
3. Budker, D., Kimball, D. F. J., Optical Magnetometry. Cambridge University Press (2013).
4. Blumenthal, D., Photonic integration for UV to IR applications. APL Photonics 5, 020903 (2020).
5. Niffenegger, R.J., Stuart, J., Sorace-Agaskar, C. et al. Integrated multi-wavelength control of an ion qubit. Nature 586, 538–542 (2020).

KEYWORDS: Quantum; photonic integrated circuits; quantum sensors; lasers; photonics; quantum sensor

OSD232-D02 TITLE: Manufacturable High-Performance Magnetometers

OUSD (R&E) CRITICAL TECHNOLOGY AREA(S): Biotechnology; Quantum Science

The technology within this topic is restricted under the International Traffic in Arms Regulation (ITAR), 22 CFR Parts 120-130, which controls the export and import of defense-related material and services, including export of sensitive technical data, or the Export Administration Regulation (EAR), 15 CFR Parts 730-774, which controls dual use items. Offerors must disclose any proposed use of foreign nationals (FNs), their country(ies) of origin, the type of visa or work permit possessed, and the statement of work (SOW) tasks intended for accomplishment by the FN(s) in accordance with the Announcement. Offerors are advised foreign nationals proposed to perform on this topic may be restricted due to the technical data under US Export Control Laws.

OBJECTIVE: Develop an accessible, high-performance scalar gradiometric magnetometer that can be reliably produced. The device architecture should focus on simplifying and streamlining the manufacturing of a scalar gradiometric magnetometer that already meets DoD-relevant performance specifications.

DESCRIPTION: The DoD has a need for magnetometers for applications such as magnetic navigation, magnetic anomaly detection, and medical imaging such as magnetoencephalography (MEG) and magnetocardiography (MCG). Quantum magnetometers, specifically optically pumped magnetometers (OPMs) [1], have advanced significantly in recent years and surpassed conventional sensors and superconducting quantum interference devices (SQUIDs). The most sensitive OPMs require extensive magnetic shielding [2], but recently, scalar gradiometric magnetometers capable of operating in Earth's field have been demonstrated with similar sensitivities [3]. Though significant advances have been made in the performance of scalar gradiometric magnetometers, one aspect that prevents their widespread use is their manufacturability. For DoD-relevant missions, there is a need for a manufacturable scalar gradiometer that can be deployed across a variety of domains and at large scale. The goal of this program is to streamline the production of high-performance scalar gradiometric magnetometers. The device should be a complete, fieldable product, including but not limited to electronics, sensor head, laser, etc.

PHASE I: This topic is accepting Direct to Phase II proposals only. To qualify for Direct to Phase II, sufficient evidence of a previous externally funded effort that specifically addresses high performance optically pumped scalarmagnetometers should be demonstrated. The scalar magnetometer should have a sensitivity of 20 fT/rtHz, a sensor head size of roughly 15 mm x 15 mm x 7 cm and operate in an ambient magnetic field of up to 100 uT. The power consumption, electronics, data rate, bandwidth, temperature operation range, and gradient and total field range, sensitivity, and accuracy should be discussed.

PHASE II: Redesign and build at least 5 optically pumped scalar magnetometers with specifications descried in Phase 1. Clear advancements in manufacturability should be demonstrated indicating the capability for mass manufacturing. Demonstrated metrics for manufacturability should include but not be limited to cost (<$5000), fabrication timelines (<3 months), and yield (>80%). Phase II Base amount must not exceed $1,300,000 for a 24-month period of performance and the Option amount must not exceed $650,000 for a 12-month period of performance.

PHASE III DUAL USE APPLICATIONS: This technology can be used for multiple military technologies such as magnetic anomaly detection or magnetic navigation but has a dual use for medical applications such as magnetoencephalography or magnetocardiography.

REFERENCES:

1. Budker, D., Kimball, D. F. J., Optical Magnetometry. Cambridge University Press (2013).

2. Kominis, I., Kornack, T., Allred, J. et al. A subfemtotesla multichannel atomic magnetometer. Nature 422, 596–599 (2003).
3. Lucivero, V.G. and Lee, W. and Limes, M.E. and Foley, E.L. and Kornack, T.W. and Romalis, M.V., Femtotesla Nearly-Quantum-Noise-Limited Pulsed Gradiometer at Earth-Scale Fields. Phys. Rev. Appl. 18, L021001 (2022).

KEYWORDS: Magnetometry; magnetic navigation; scalar gradiometry; scalar magnetometry; quantum magnetometer

OSD232-003 TITLE: Efficient Integration or Direct Growth on SOI of Foundry-Scale CMOS Compatible Second Order Nonlinear Materials and/or Short-Wavelength Photonic Materials with Low Optical Loss

OUSD (R&E) CRITICAL TECHNOLOGY AREA(S): Quantum Science

OBJECTIVE: Development of a foundry-compatible, direct growth in a Silicon on insulator (SOI) stack, second-order nonlinear material that can be that can be used for photon conversion and low loss waveguides.

DESCRIPTION: Silicon on insulator (SOI) has been a growing standard platform for foundry-scale (300mm) integrated photonics. In that platform modulation and switching are done with mainly with thermal or carrier injection-based devices since silicon's crystalline structure is centrosymmetric and therefore does not have a second-order nonlinearity. These methods of modulation are either slow (thermal) or lossy (carrier injection) and for low loss demanding applications such as quantum photonics make the systems tough to scale. Secondly, for quantum or frequency conversion applications silicon or silicon nitride gives no native access to the second order nonlinearity (unless acquired through electric field induced changes or strain tuning) and therefore must rely on the weaker third order nonlinearity. The ability to have a second order nonlinear material would allow for efficient photon generation/conversion, as well as high speed low-loss optical modulation for classical and quantum applications. The goal of this effort is to identify, develop, and demonstrate second order nonlinear materials that operate in the visible and infrared (400-1700nm) and can be directly integrated with the foundry scale SOI platform.

PHASE I: Identify a set of second order nonlinear materials that are foundry compatible with the 300mm SOI platform. Demonstrate on the small scale (<300mm) the integration of these materials on an SOI platform. The information and research conducted during the Phase 1 will be delivered as a final report. Phase I Base amount must not exceed $295,000 for a 12-month period of performance.

PHASE II: Demonstration of the integration of foundry capable second order nonlinear materials on the 300mm SOI platform. The required deliverables for the demonstration are analysis and data of the material quality on the SOI platform, development and demonstration of devices that show the modulation and switching capabilities of the material, and development and demonstration of devices that show nonlinear photon generation and conversion. The samples will be delivered to the DoD for further analysis along with a plan to transition to a foundry. Phase II Base amount must not exceed $1,300,000 for a 24-month period of performance and the Option amount must not exceed $650,000 for a 12-month period of performance.

PHASE III DUAL USE APPLICATIONS: The resulting efforts under Phase II can be transitioned to commercial applications for high-speed data encoding for optical communication applications, and lidar applications. These applications are relevant as well to the DoD. The research can be transitioned for the use of entangled photon generation for quantum communication, quantum networking, entanglement distribution, and quantum computing.

REFERENCES:

1. Lu, T.J., Fanto, M., Choi, H., Thomas, P., Steidle, J., Mouradian, S., Kong, W., Zhu, D., Moon, H., Berggren, K. and Kim, J., 2018. Aluminum nitride integrated photonics platform for the ultraviolet to visible spectrum. Optics express, 26(9), pp.11147-11160.
2. Fan, R., Lin, YY., Chang, L. et al. Higher order mode supercontinuum generation in tantalum pentoxide (Ta2O5) channel waveguide. Sci Rep 11, 7978 (2021).

KEYWORDS: Integrated photonics; second-order nonlinearity; optical waveguides; foundry compatible; low loss waveguides; visible integrated photonics

OSD232-D04 TITLE: Gravity Gradiometer Demonstration on an Inertial Platform

OUSD (R&E) CRITICAL TECHNOLOGY AREA(S): Quantum Science

OBJECTIVE: This project will demonstrate the operation of a single-axis gravity gradiometer with a noise floor below at approximately 10 Eotvos (or similar performance if already demonstrated) on a moving platform in environments where vibrations, accelerations, rotations, and temperature swings cannot be neglected.

DESCRIPTION: Atomic gravity gradiometers are quantum sensors that offer state-of-the-art performance under laboratory conditions [1]. Compared to existing classical approaches, they offer superior sensitivity and reduced size, weight, and power (SWaP). However, their operation is currently limited to static or quasi-static environments achieved through environmental isolation. Dynamic environments present challenges that have hampered the commercialization of devices for fielded operation [2,3].

This solicitation seeks a robust single-axis gravity gradiometer (GG) prototype with performance and SWaP comparable to state-of-the-art atomic devices (10 Eotvos or similar performance if already demonstrated, where 1 E= 10^{-9} second^{-2}) but capable of operation in environments where vibrations, acceleration and rotations may be present. In contrast to gravimeters, GGs enable common mode rejection of certain platform motions, reducing the time averaging required to detect anomalous mass distributions. Therefore, GGs offer advantages over gravimeters for certain applications such as the detection of underground features (e.g. tunnels or voids). Furthermore, these devices can augment inertial navigation systems by distinguishing between gravitational and inertial acceleration.

Ideally, this sensor will have a clear path to commercialization, relying on few, if any, precision-machined components. While this effort is expected to require integration into an inertially stabilized platform, proposers are encouraged to offer innovative concepts that explore cutting-edge physics to solve the challenges of fielding gravity gradiometers.

PHASE I: This topic is accepting Direct to Phase II proposals only. Documentation to determine if Phase I feasibility has been met:

- Existing operational GG hardware with a path to meet the Phase II metrics
- Demonstrated acceleration accuracy less than 10 microGal
- GG integrates to under 200 E within 1000 seconds
- Total system volume of less than 50 L
- Weight less than 50 kg
- Power consumption less than 200 W

PHASE II: The gravimeter developed in this effort shall measure the spatial gradient of the vertical component of gravity along the vertical direction (i.e. the Gzz component of the tensor, where z is the surface normal). Phase II Base amount must not exceed $1,450,000 for a 24-month period of performance and the Option amount must not exceed $250,000 for a 12-month period of performance.

The base portion of Phase II will develop a device that can operate as a GG in the presence of motion. It should meet or exceed the following metrics:

- Acceleration measurement precision of 10 microGal / rt(Hz)
- Short term GG sensitivity of less than 50 E / rt(Hz)
- GG statistical uncertainty of 5 E within 600 seconds of averaging
- Total system volume (including any inertial stabilization) less than 40 L
- Weight less than 30 kg
- Power consumption less than 150 W

These specs must be met under environmental test conditions consisting of:

- Rotations up to 15 deg/s
- Accelerations within +/- 0.1 g of local gravity
- Random vibrations of 0.5 grms
- Operating temperatures between -10 and 40 degC

This will entail a thorough analysis of the sensor performance in the presence of dynamics with the appropriate mitigations in place.

The Phase II option period will focus on a vehicle demonstration. The device must therefore be self-contained, and mobile enough to be loaded onto an appropriate vehicle. The vehicle can be assumed to provide standard wall-plug power.

PHASE III DUAL USE APPLICATIONS: GG capable of fielded operation on a moving platform would have dual-use applications in mineral, oil, and gas exploration, civil engineering, gravity mapping, hydrology, and geophysics.

REFERENCES:

1. M. J. Snadden, J. M. McGuirk, P. Bouyer, K. G. Haritos, and M. A. Kasevich, “Measurement of the Earth's Gravity Gradient with an Atom Interferometer-Based Gravity Gradiometer,” Phys. Rev. Lett. 81, 971 (1998).
2. B. Stray et al., “Quantum sensing for gravity cartography,” Nature 602, 590 (2022).
3. C. Janvier, “A compact differential gravimeter at the quantum projection noise limit,” arXiv 2201.03345 (2022).

KEYWORDS: Atom Interferometry; Gravity Gradiometer; Fieldable Quantum Sensor

OSD232-D05 TITLE: Rydberg-Atom-Compatible Alkali-Metal Vapor Cells with Nontraditional Geometries

OUSD (R&E) CRITICAL TECHNOLOGY AREA(S): Integrated Sensing and Cyber; Integrated Network Systems-of-Systems; Quantum Science

OBJECTIVE: Develop rubidium and cesium vapor cells with a thin rectangular geometry that are compatible with the excitation of Rydberg atomic states.

DESCRIPTION: Vapor cells containing dilute gaseous samples of alkali metals (particularly cesium and rubidium) are a critical component in many quantum technologies relevant to the DoD mission. In particular, quantum electric field sensors based on highly excited Rydberg atomic states in thermal vapors are an emerging platform for receiving radio-frequency communications, calibrating antennas, and imaging teraHertz-frequency (THz) electromagnetic sources. Cell geometries beyond traditional cubic and cylindrical designs will be advantageous for optimizing sensor performance and extending the technology's applications.

Reliably obtaining vapor cells with nontraditional geometries that are also capable of supporting excitation to Rydberg states is an ongoing challenge for DoD researchers. Producing vapor cells with consistent alkali vapor pressures, low permeability, and appropriate optical coatings is already something of an art form. Highly reactive rubidium precludes using many materials for enclosures, coatings, and integrated structures. Moreover, alkali metal tends to deposit on inner surfaces, reducing transmission of probing laser beams and creating a Faraday cage that shields low-frequency electromagnetic fields. The ability to excite Rydberg levels is a further challenge due to the various optical wavelengths involved and their propensity to induce unwanted charging on cell surfaces, which perturbs the atoms. Even in cells that support stable ground-state populations, collisions of Rydberg atoms with background gasses, interactions with surface charges, and other chemical reactions can suppress excitations to Rydberg states. The goal of this SBIR is to foster reliable development and delivery of rubidium and cesium vapor cells with rectangular geometry that are compatible with the excitation of Rydberg atomic states. Accomplishing this will require investments in cell design, bonding and fabrication techniques, sample filling process development, and quality assurance testing to verify Rydberg state excitation capability. Many existing research efforts have focused on creating compact cells, however, maintaining the capability to excite atoms to Rydberg states introduces additional constraints in the fabrication process and materials. A thin rectangular form factor with thin (<2mm) walls could allow efficient coupling of signals from planar resonant circuits or photonic integrated circuits. Such a geometry would also facilitate spatially-resolved THz imaging with Rydberg sensors over larger areas than are currently feasible without requiring the cell to be physically repositioned over the object to be imaged.

PHASE I: This topic is accepting Direct to Phase II proposals only. Documentation of existing alkali vapor cell production (though not necessarily those compatible for Rydberg-state excitation) and sales for scientific applications will be sufficient to establish feasibility. Data demonstrating the capability to measure resonant absorption of typical alkali optical spectroscopy (atomic absorption spectroscopy) in cells at the small business is preferred.

PHASE II: The project will produce 10-100 rubidium or cesium vapor cells of a high-aspect-ratio rectangular geometry to a government laboratory for testing. The cells must demonstrate over 40% room-temperature resonant absorption of probing light and support excitation to Rydberg atomic states. The walls on the long axis of the cell must be optically transparent and flat to accommodate laser beam transmission. The large-area walls (>6 cm^3) must be transparent to electromagnetic waves with frequencies of 0.1 – 3.0 terahertz (THz).

The cells will be tested by the government to determine adequate Rydberg sensor performance based on measurement of narrow unperturbed atomic resonances and transparency to agreed electromagnetic frequencies.

Optional deliverable requirements include: Minimum alkali optical thickness or vapor pressure, wall material choice (e.g. borosilicate glass with sapphire coating), optical access, window transparency and optical quality. Vapor density control that is RF transparent, waveguide and/or electrode integration, surface charge mitigation, integrated micro-optics or fiber coupled cells, aging tests. Phase II Base amount must not exceed $1,000,000 for a 12-month period of performance and the Option amount must not exceed $700,000 for a 12-month period of performance.

PHASE III DUAL USE APPLICATIONS: Creating a reliable process for filling alkali vapor cells that support Rydberg state excitation and have non-traditional geometries will have applications for quantum sensing in a variety of military and commercial spaces. Rydberg-atom electrometers are an emerging technology for creating communication receivers simultaneously operating at frequencies spanning many tens of GHz in a single device. This could have applications in the defense and commercial telecommunication industries, to include 5G technology. Rydberg-atom electrometers can also be used to calibrate antenna emissions in a way that does not perturb the radiation pattern and that is ambivalent to strong fields that could damage traditional technologies.

REFERENCES:

1. Phys. Rev. Applied 13, 054034 (2020) - Vapor-Cell-Based Atomic Electrometry for Detection Frequencies below 1 kHz (aps.org)
2. Phys. Rev. X 10, 011027 (2020) - Full-Field Terahertz Imaging at Kilohertz Frame Rates Using Atomic Vapor (aps.org)

KEYWORDS: Vapor; cell; rubidium; cesium; Rydberg; quantum; atomic; teraHertz

OSD232-006 TITLE: Low Size, Weight, and Power (SWAP), High Electrical Efficiency Microwave and/or Radiofrequency (RF) Generator or Amplifier for Atomic or Molecular Spectroscopy Applications

OUSD (R&E) CRITICAL TECHNOLOGY AREA(S): Microelectronics; Quantum Science

OBJECTIVE: Low Size, Weight, and Power (SWaP), high electrical efficiency microwave and/or radiofrequency (RF) generator or amplifier for atomic or molecular spectroscopy applications.

DESCRIPTION: Quantum computing and quantum information science use “qubits” (quantum bits) to store information. These qubits can be implemented in many ways, frequently by manipulating the energy state of the qubit to change between two levels. For atomic, atomic ion[1,2], molecular ion, and other physical implementations of qubits, these levels can be separated by microwave-scale energy differences. For example, trapped ion qubits can have level differences ranging from 0.8 to 41 GHz (listed as hyperfine splittings in [3]). Additionally, radio frequency can be utilized with acousto-optic or electro-optic modulation to place sidebands on lasers, allowing them address additional structure within the qubits. Microwave spectroscopy is not limit to single atoms or ions, but can extend to molecular polar ions [4] where microwaves are able to identify and manipulate the rotational state of the ions.
This need places good quality microwave and radiofrequency sources and amplifiers among the critical components of many quantum information science-related experiments. In particular these devices need good amplitude, frequency, and phase noise characteristics for the final, post-amplification signal at delivered to the qubit.

While most of these experiments take place in laboratory environment, increased electrical efficiency remains important. In addition to their contributions to operating costs, electrical inefficiencies will add to the overall thermal load of the laboratory making temperature stability a greater challenge and restricting the locations of the equipment relative to temperature-sensitive equipment. Additionally, for efforts looking to transition these quantum technologies outside of pristine laboratory environments, the Size, Weight, and Power (SWaP) of these devices will limit the locations in which they can be deployed. Mobile platforms are a particular challenge due to their strict SWaP limitations; on these platforms any gain in efficiency or reduction in SWaP either allows additional capabilities to be included or enables longer time-in-service. For example (although not used for spectroscopy in this instance), microwave sources were deployed to the International Space Station as part of a ultracold atomic physics experiment package [5].

PHASE I: Phase I will determine the technical feasibility of radiofrequency and/or microwave sources and/or amplifiers, suitable for the uses described in the objective and description above. Because this topic covers a wide range of frequencies and applications, no uniform set of metrics will apply to all situations. As such, the proposer should identify one or more comparable research laboratory-grade device(s) as the benchmark for comparison during Phase I and any following Phase efforts.
A successful effort will include a detailed analysis of predicted performance, including both improvements on relevant microwave and/or radiofrequency signal metrics (e.g. linearity, gain, response flatness, phase noise, amplitude noise, frequency noise, etc.) and overall electrical efficiency of the system compared to identified performance benchmarks. Phase I Base amount must not exceed $295,000 for a 12-month period of performance.

PHASE II: Using the results from Phase I, develop, test, and demonstrate the operation of a prototype system. This should include a direct laboratory comparison to the identified benchmark system in Phase I, if feasible. Phase II Base amount must not exceed $1,300,000 for a 24-month period of performance and the Option amount must not exceed $650,000 for a 12-month period of performance.

PHASE III DUAL USE APPLICATIONS: The quantum information science industry extends well beyond DoD research settings, with many existing laboratories in DoD, academic, and private industry contexts (for example, [6] contains a listing of trapped ion research groups around the world). These laboratories have uses for microwaves beyond those considered in this SBIR, for example [7-8]. Any gains in performance under Phase I or Phase II could be utilized by any of these laboratories. Additionally, microwaves are used broadly throughout the telecommunications industry, where improvement in efficiency could provide immediate benefits to interested parties.

REFERENCES:

1. Colin D. Bruzewicz, John Chiaverini, Robert McConnell, and Jeremy M. Sage , "Trapped-ion quantum computing: Progress and challenges", Applied Physics Reviews 6, 021314 (2019) https://doi.org/10.1063/1.5088164
2. Leibfried, D., Blatt, R., Monroe, C., & Wineland, D. (2003). Quantum dynamics of single trapped ions. Reviews of Modern Physics, 75(1), 281–324. doi:10.1103/RevModPhys.75.281
3. Quantum Computing with Trapped Ions, Duke University. (2023). Trapped Ion Periodic Table. Retrieved March 10, 2023, from https://iontrap.duke.edu/resources/ion-periodic-table/
4. Shi, M., Herskind, P. F., Drewsen, M., & Chuang, I. L. (2013). Microwave quantum logic spectroscopy and control of molecular ions. New Journal of Physics, 15(11), 113019. doi:10.1088/1367-2630/15/11/113019
5. Frye, K., Abend, S., Bartosch, W. et al. The Bose-Einstein Condensate and Cold Atom Laboratory. EPJ Quantum Technol. 8, 1 (2021). https://doi.org/10.1140/epjqt/s40507-020-00090-8
6. Air Force Research Laboratory, Quantum Information Science Branch. (2022). AFRL/RITQ - ion references and useful links. AFRL/RITQ - Ion References and Useful Links. Retrieved March 10, 2023, from https://www.afrl.af.mil/About-Us/Fact-Sheets/Fact-Sheet-Display/Article/3040329/afrlritq-ion-references-and-useful-links/
7. Lekitsch, B., Weidt, S., Fowler, A. G., Mølmer, K., Devitt, S. J., Wunderlich, C., & Hensinger, W. K. (2017). Blueprint for a microwave trapped ion quantum computer. Science Advances, 3(2), e1601540. doi:10.1126/sciadv.1601540
8. Piltz, C., Sriarunothai, T., Ivanov, S. S., Wölk, S., & Wunderlich, C. (2016). Versatile microwave-driven trapped ion spin system for quantum information processing. Science Advances, 2(7), e1600093. doi:10.1126/sciadv.1600093

KEYWORDS: Microwave Oscillators; Microwave Amplifiers; Radio Frequency Generators; Radio Frequency Amplifiers; Radio Frequency Spectroscopy; Atomic Spectroscopy; Molecular Spectroscopy; Quantum Information

OSD232-D07 TITLE: Robust Resonant rf Circuit for Trapped Ion Systems

OUSD (R&E) CRITICAL TECHNOLOGY AREA(S): Quantum Science

OBJECTIVE: This program seeks to develop a stable, resonant rf circuit for trapped ion systems that is resistant to environmental perturbations such as ambient temperature changes and vibration.

DESCRIPTION: Isolated, trapped atomic ions are among the leading candidates to realize quantum computing and quantum networking systems. Trapped ions are confined using high voltage rf electric fields to isolate the ions from the external environment. The confining potential determines the normal mode frequencies of vibration of a chain of trapped ions; typical rf resonant circuits (Q = 200 – 500) apply a single frequency in the 10 – 100 MHz range with an rf amplitude of approximately 250 – 500 volts, depending on the ion trap. Stabilizing the trapped ion normal mode frequencies, proportional to the ratio of the applied voltage to the rf drive frequency, can play a key role in enabling high-fidelity entangling gates between trapped ions while allowing higher speed entangling gates. Using active feedback, these circuits have been stabilized to approximately 10 ppm in a pristine, laboratory setting with small variations in temperature and minimal vibration [1].

PHASE I: This topic is accepting Direct to Phase II proposals only. The proposer must provide a report or documentation showing the feasibility of the proposed approach. Such a report could be based on measured performance of an early prototype device (whether connected to an ion-trap stand-in load or an ion trap). If iterating on an existing design with measured performance lower than the specifications below, offeror should identify the key design changes leading to the expected improvement in performance, along with applicable simulation and/or modeling. For new designs, the approach should be documented with simulations and/or modeling showing the expected performance for the proposed design.

PHASE II: This project will develop a laboratory prototype device (not necessarily a quarter wave helical resonator) that results in an applied rf field to an ion trap where a trapped ion's secular frequency should be stable. To accomplish this, the ratio of the rf voltage amplitude to the drive frequency should vary by less than 1 x 10^-5 if the ambient air temperature varies by +/- 3 C. This stability should also be maintained if the device is subjected to acoustic noise in the audio range at levels of approximately 60 dB. The resonator shall be tested by measuring the stability of an ion trap's transverse secular frequency. The measurement should be performed optically by probing an ion sideband of motion probing a narrow transition (ex: Raman or quadrupole) to enable the required precision for characterizing the resonator performance. This measurement can be done in-house or by external partnership. In addition, a final report detailing the design and testing should be made available. This report could take the form of a publication if appropriate. Phase II Base amount must not exceed $700,000 for a 12-month period of performance and the Option amount must not exceed $300,000 for a 6-month period of performance.

PHASE III DUAL USE APPLICATIONS: Phase III potential applications: This rf resonator circuit with enhanced resistance to environmental perturbations can be commercialized and used on commercial trapped ion systems as well as DoD trapped ion systems. The development of trapped ion systems is aligned with DoD goals to develop quantum information technology to enhance position, navigation, timing, and secure communication. Generally, this technology could be used where there is a need to supply high voltage at radiofrequencies to a low impedance electrical load.

REFERENCES:

1. “Active Stabilization of Ion Trap Radiofrequency Potentials,” K. G. Johnson, J. D. Wong-Campos, A. Restelli, K. A. Landsman, B. Neyenhuis, J. Mizrahi, and C. Monroe, Rev. Sci. Instrum. 87, 053110 (2016); arXiv:1603.05492v2

2. “Electromagnetic traps for charged and neutral particles”, W. Paul, Rev. Mod. Phys, 62, 531,(1990).
3. “Realization of a Filter with Helical Components”, A. I. Zverev and H. J. Blinchikoff, IRE Trans. Compon. Parts, 99 (1961).
4. “Coaxial Resonators with Helical Inner Conductor,” W. W. MacAlpine and R. O. Schildknecht, Proc. IRE, 2099 (1959).
5. Siverns, J.D., Simkins, L.R., Weidt, S. et al. On the application of radio frequency voltages to ion traps via helical resonators. Appl. Phys. B 107, 921–934 (2012).; arXiv:1106.5013v3

KEYWORDS: Ion trap; entanglement; quantum gates; rf resonator; high-fidelity; quantum computing; quantum network

OSD232-008 TITLE: Efficient, Scalable, and Robust Techniques for Interconnecting Optical Fibers and Photonic Integrated Circuit Waveguides at Milli-Kelvin Temperature

OUSD (R&E) CRITICAL TECHNOLOGY AREA(S): Integrated Sensing and Cyber; Integrated Network Systems-of-Systems

OBJECTIVE: To develop techniques for efficient, reliable, and extensible routing of light from ambient conditions through optical fibers to quantum photonic integrated circuit waveguides at milli-Kelvin temperature.

DESCRIPTION: Future quantum information networks will enable new capabilities for the DoD in regard to secure communications, information processing, sensing, positioning, navigation and timing. To achieve such functionality, these networks will require heterogeneous node technology, with different quantum technologies serving different functions – e.g. memory, processor, sensor, transceiver, and transducer devices. Accordingly, to realize such functionality efficient quantum interfaces must be developed between different qubit modalities, including technologies that work in the microwave domain and ones that primarily work at optical frequencies. As well, because microwave-regime quantum technologies (like superconducting and semiconducting qubits and quantum sensors), generally must be operated at cryogenic temperatures, efficient quantum interconnects between microwave and optical frequencies must be able to satisfy the engineering demands that derive from thermal gradients, heat loads, signal attenuation, and thermal cycling between ambient conditions and Kelvin and milli-Kelvin temperatures. A particularly critical and outstanding requirement in this regard is the engineering of efficient, reliable, and scalable (i.e. high density) interconnects between optical fibers and quantum integrated photonic circuit (QPIC) waveguides, transducers, detectors, and other QPIC elements that remain robust (i.e. continue to achieve key performance parameters) in the presence of differential thermal contraction and other variations due to temperature dependent materials parameters of optical fibers, adjoining media, and QPICs. Among other considerations, this requirement is essential for coherent quantum state transduction and heralded entanglement between cryogenic quantum processors on physically separated cryostats, efficient routing of light to superconducting photon sensors, and high throughput i/o data channels for classical electro-optical cryogenic signal routing and processing. In light of this, the call for proposals is seeking innovative technologies and/or processes thar will advance the development of low-loss cryogenic fiber interconnects to QPICs.

The main objective is to obtain sub-dB coupling loss per connection to temperatures as low as 10 milli-Kelvin, typical of standard commercially available dilution refrigerators, with low-loss performance maintained over hundreds of thermal cycles. Moreover, the techniques should be compatible with a modular and extensible milli-kelvin platform, which entails the follow characteristics: small form factor, readily enabling installation of multi-converter units in a single cryostat; minimal need for tuning of interconnects after cool-down from ambient conditions (no tuning is the ideal target to achieve); and compatibility with state-of-the-art superconducting and semiconductor qubits and sensors for chip-level microwave-optical integration. While these techniques or processes may be at low technology readiness levels (e.g. TRL 3) by the end of Phase I, it is expected that a pathway to TRL maturation will be achieved through Phase II, with the potential for integration with heterogeneous quantum entanglement distribution testbeds in Phase III.

PHASE I: Validate the product-market fit between the proposed solution and the proposed topic and define a clear and immediately actionable plan for running a trial with the proposed solution and the proposed AF customer. This feasibility study should:

1. Clearly identify who the prime (and additional) potential end user (e.g. Air Force, Army, etc.) is and articulate how they would use your solutions (i.e., the one who is most likely to be an early adopter, first user, and initial transition partner).

2. Deeply explore the problem or benefit areas, which are to be addressed by the solutions - specifically focusing on how this solution will impact the end user of the solution.
3. Define clear objectives and measurable key results for a potential trial of the proposed solution with the identified end users.
4. Clearly identify any additional specific stakeholders beyond the end users who will be critical to the success of any potential trial. This includes, but is not limited to, program offices, contracting offices, finance offices, information security offices and environmental protection offices.
5. Describe the cost and feasibility of integration with current mission-specific products.
6. Describe if and how the demonstration can be used by other DoD or governmental customers.
7. Describe technology related development that is required to successfully field the solution.
8. The funds obligated on the resulting Phase I STTR/SBIR contracts are to be used for the sole purpose of conducting a thorough feasibility study using scientific experiments, laboratory studies, commercial research and interviews. Prototypes may be developed with STTR/SBIR funds during Phase I studies to better address the risks and potential payoffs in innovative technologies.

Phase I Base amount must not exceed $295,000 for a 12-month period of performance.

PHASE II: Develop, integrate, and demonstrate a prototype system determined to be the most feasible solution during the Phase I feasibility study. This demonstration should focus specifically on:

1. Evaluating the proposed solution against the objectives and measurable key results as defined in the Phase I feasibility study.
2. Describing in detail how the solution can be scaled to be adopted widely (i.e. how can it be modified for scale).
3. A clear transition path for the proposed solution that takes into account input from all affected stakeholders including but not limited to: end users, engineering, sustainment, contracting, finance, legal, and cyber security.
4. Specific details about how the solution can integrate with other current and potential future solutions.
5. How the solution can be sustainable (i.e. supportability).
6. Clearly identify other specific DoD or governmental customers who want to use the solution.

Phase II Base amount must not exceed $1,130,000 for a 24-month period of performance and the Option amount must not exceed $840,000 for a 12-month period of performance.

PHASE III DUAL USE APPLICATIONS: Advancements of this technology would be of direct relevance to the DoD for construction and operation of heterogeneous quantum networking testbeds for studying the use of entanglement distribution for new capabilities in secure communications, information processing, sensing, positioning, navigation and timing. It would also have direct relevance to industry, including providing efficient means for the scaling of existing cryogenic components of commercial quantum processors.

REFERENCES:

1. United States Air Force 2030 Science and Technology Strategy: Strengthening USAF Science and Technology for 2030 and Beyond. https://www.af.mil/Portals/1/documents/2019%20SAF%20story%20attachments/Air%20Force%20Science%20and%20Technology%20Strategy.pdf
2. A Coordinate Approach to Quantum Networking Research https://www.quantum.gov/wp-content/uploads/2021/01/A-Coordinated-Approach-to-Quantum-Networking.pdf

3. Defense Science Board. Applications of Quantum Technologies https://dsb.cto.mil/reports/2010s/DSB_QuantumTechnologies_Executive%20Summary_10.23.2019_SR.pdf

KEYWORDS: Quantum communication; quantum information processing; quantum interconnects; transduction; quantum photonic integrated circuits; QPICS; superconducting qubits; superconducting sensors

OSD232-009 TITLE: Application-specific Electronic Package for a Quantum Sensor

OUSD (R&E) CRITICAL TECHNOLOGY AREA(S): Microelectronics; Quantum Science

OBJECTIVE: An application-specific electronics package that enables low-noise miniaturization of quantum systems.

DESCRIPTION: Quantum systems rely on electronics for control and signal input/output to larger systems. Often, these originate with large scale lab electronics, then are scaled down to field programmable gate arrays (FPGA) to enable modularity. However, FPGAs can be large, expensive, power hungry, and potentially introduce unknown and undesired threats. Application-specific electronics can be one approach to overcoming the limitations of an FPGA. Application specific electronics can include, but are not limited to, custom printed circuit board design or application-specific integrated circuit (ASIC) development. An ASIC is the smallest SWaP and typically lowest noise solution but has a high barrier to entry as it includes high non-recurring engineering costs and long wait times, due to the business model of IC foundries. This SBIR topic aims to lower the investment required by small businesses to creating custom, specific electronics and packaging for quantum sensors, in order to increase TRL and the ability to bring small quantum sensors to market.

PHASE I: Use of IC foundries can be arduous and include long lead times. Phase I of the topic should include design of the application specific electronics, identifying and negotiating with a trusted IC foundry for fabrication, and receiving the process design kit (PDK) from the foundry of choice. The outcome of Phase I should be that the performer is ready to move forward to procure an ASIC with a foundry, either with dedicated wafers or as part of a multi-project wafer (MPW) run.

Alternatively, Phase 1 can be to develop application specific, custom electronics on a printed circuit board. The product of Phase I is a detailed report outlining the design, including modeling and simulation, and a detailed plan for fabrication. One key component for this critical technology, will be to consider the ‘trust’ of the vendor. The Phase I deliverable should outline the risk management and quality assurance of safeguarding against any IP threats. Phase I Base amount must not exceed $290,000 for a 12-month period of performance.

PHASE II: The Phase II goal of the SBIR is to integrate and demonstrate the custom electronics packaged with and operating with the quantum sensor of choice. The Phase II deliverable is a report outlining the electronics design and fabrication, as well as integration tests and demonstration results. Ideally, the custom electronics integrated with a quantum sensor will become a government off-the-shelf component for procurement. The custom, packaged electronics should dramatically reduce cost, size, weight and power necessary for operating quantum sensors, thereby creating a viable transition path to the warfighter. Phase II Base amount must not exceed $1,000,000 for a 24-month period of performance and the Option amount must not exceed $900,000 for a 12-month period of performance.

PHASE III DUAL USE APPLICATIONS: One military application would be to create the custom electronics necessary for a quantum-based clock, such as a photonic integrated chip that requires IC fabrication for photonics and electronics. The product to be included with the quantum clock, would require packaging. Alternatively, there are chip-scale quantum sensors, such as SQUID arrays that require custom electronics packaging and electronic interfaces. This SBIR topic covers the electronics design, fabrication, and packaging for this class of EM sensor.

REFERENCES: Charbon, E. Cryo-CMOS Electronics For Quantum Computing: Bringing Classical Electronics Closer To Qubits In Space And Temperature. IEEE Solid-State Circuits Magazine 13, 54–68 (2021).

KEYWORDS: Quantum; atomic; asic; low-swap; quantum sensor; packaging