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Quantum Science and Technology



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Abstract

Remarkable advancements in the ability to create, manipulate, and measure quantum systems are paving the way to build next generations of devices based on quantum physics. Quantum technologies in Russia are on the list of strategically important cross-cutting directions in the framework of the National Technology Initiative programs and the Digital Economy National Program. The broad focus includes quantum computing and simulation, quantum communications, quantum metrology and sensing. This paper reviews existing research on quantum science and technologies in Russia and summarizes the main goals for the next few years that form the basis of an upcoming major national initiative.

Introduction and background

Quantum technology, an umbrella field covering quantum computing, quantum simulation, quantum communications, quantum metrology and sensing, are now under active development across the world. Modern quantum technologies build on achievements of fundamental science during the 20th century. Soviet and Russian scientists have been developing cornerstones of quantum technologies for many decades. Remarkable breakthroughs include the development of lasers (N G Basov and A M Prokhorov, Nobel Prize in 1964), developing semiconductor heterostructures used in high-speed- and optoelectronics (Z I Alferov, Nobel Prize in 2000), and achievements in the field of low-temperature physics, outstanding results in the study of superfluidity and superconductivity (P L Kapitza, Nobel Prize in 1978; L D Landau, Nobel Prize in 1962, V L Ginzburg and A A Abrikosov, Nobel Prize in 2003). Many of the ongoing research and industrial activities in quantum technologies would have been impossible without these Russian results. This heritage forms a perfect basis for further success in quantum science and technologies in Russia.

Quantum research in Russia is supported by both governmental and industrial entities in a variety of formats. In 2010, a private research institution for conducting fundamental and applied research in modern quantum physics and technologies, the Russian Quantum Center (RQC), was founded on the territory of the Skolkovo Foundation. In total more than 2 billion rubles (~30M EUR) have been secured through competitive grants and from private investments from one of the country's largest bank—Gazprombank. In 2014, Kazan Quantum Center under the umbrella of the Kazan National Research Technical University was formed. Additionally, two National Technological Initiative (NTI) centers created in 2017–2018: NTI Quantum

Technologies Centre at M.V. Lomonosov Moscow State University (QTC MSU) and NTI Center for Quantum Communications at the National University of Science and Technology MISiS, are a part of the Russian government's program to support of quantum technologies. These centers of excellence are supported by the Ministry of Science and Higher Education of the Russian Federation and Russian Venture Company with approximately 2 billion rubles (~30M EUR) 5 year-budget for each center. Their ongoing activities are related to research, developing quantum devices with subsequent commercialization, and creating new educational programs. In the field of quantum computing, collaborative projects on developing quantum computing devices based on superconducting circuits, neutral atoms, and photons have been initiated by Russia's Foundation for Advanced Research and Rosatom.

Further funding is channeled through the Megagrants program, in which a single internationally renowned researcher is provided a grant on a scale of 3–5M EUR to establish a group at a Russian university. While Megagrants are offered in all fields of science, they have been instrumental in attracting and supporting dozens of outstanding quantum scientists to Russia. Most fundamental research projects in quantum technologies are supported by Russian Foundation for Basic Research (RFBR), Russian Science Foundation (RSF), and Programs of Ministry of Science and Higher Education of the Russian Federation. The amount of these grants varies significantly: from tens of thousands of EUR for starting grants up to several million EUR for the creation of innovative laboratories.

Today Russia is at the stage of accepting a five-year roadmap for the development of quantum technologies as a part of the Digital Economy National Program, which we further refer as Russian Quantum Technologies Roadmap. Quantum technologies are in the list of nine cross-cutting directions of the National Digital Economy Program with a total announced budget around 25 billion EUR. Quantum technologies play a special role in this list since their role is to support further development of acquisition, secure communication, and processing data, which is required by all other directions. The final budget for supporting specifically quantum technologies is not yet defined, but the amount requested by experts is close to 1 billion EUR. The primary goal of this program is to consolidate ongoing research activities in four sections: (i) quantum computing and quantum simulation, (ii) quantum communications, (iii) quantum metrology and quantum sensing, and (iv) enabling technologies. More than a hundred twenty experts from leading research institutions are attracted to the work on this roadmap.

Supporting quantum technologies as the country's strategic priority has been lobbied by their future users from governmental agencies, financial institutions, and various industries. In particular, interest to quantum information processing and quantum communications comes from Rosatom, Rostech, Rostelecom, Bank of Russia, Gazprombank, Sberbank, and others. A case in point is the initiation of a research initiative on quantum machine learning by Gazprombank with an annual budget of about 1.4 million EUR. After completing the quantum technology roadmap, three state companies made commitments to the Russian Government to support specific fields: Rosatom is responsible for quantum computing, Russian Railways (RzhD) is responsible for quantum communications, and Rostech is taking lead on quantum sensing and metrology. Below we review each of these branches individually to discuss their current status and short-term goals.

Quantum computing and simulation

Several collaborative projects aimed at exploring the resources of various quantum systems in tasks related to quantum information processing and quantum simulation exist in Russia. Physical systems under active investigation include superconducting qubits, neutral atoms, ions in traps, photons, and polaritons. Experimental research projects are accompanied by intense theoretical work.

The main goal of the Russian Quantum Technologies Roadmap is building a full stack of quantum computing technologies, which results in a move from laboratory prototypes to cloud-accessible noisy intermediate-scale quantum (NISQ) devices in the next several years. The following projects in the hardware domain are paid particular attention to: superconducting quantum technologies; neutral atoms; trapped ions; photonics; polaritonics; impurity atoms. In the software domain the following directions are highlighted: quantum error correction codes; quantum error suppression methods; quantum and quantum-inspired algorithms; building large-scale systems for emulating quantum devices. creating cloud platform for access to quantum computing systems.

This big goal includes the increase in the 'quantum volume' (achieving scalability without dramatic increase in error rates). At the same time there is increasing demand in solving proof-of-concept tasks relevant for industry, for example, simulation of various systems, physical phenomena, and dynamical processes, solving optimization problems on graphs, machine learning tasks, and search problems.

Superconducting qubits. The first Russian projects on superconducting qubits were started in two experimental laboratories at National University of Science and Technology MISiS (founded in 2011) and

Moscow Institute of Physics and Technology (founded in 2014). Their research programs were supported by Ministry of Science and Higher Education via Megagrant and 5TOP100 Programs. Also, a laboratory has launched in Novosibirsk State Technical University aiming the research in the same direction. These projects were followed by a joint three-year research initiative, which was supported by the Foundation for Advanced Research, Federal Agency on Atomic Energy, and the Ministry of Science and Higher Education. This project joins the National University of Science and Technology MISiS, Moscow Institute of Physics and Technology, RQC, Bauman Moscow State Technical University, Institute of Solid State Physics RAS, N. L. Dukhov All-Russia Institute of Science and Research, and Novosibirsk State Technical University.

The main result of the present effort is the demonstration of single-qubit and two-qubit quantum gate operations, such as iSWAP, CZ, and CNOT, using several types of superconducting qubits. An important ingredient of this project is the supplemental research activity on quantum metamaterials, which is of importance for the further development of superconducting qubits as a platform not only for universal quantum computing but also for quantum simulation.

As a result of the realization of these projects, the achieved coherence time is already about 50 μs and the two-qubit fidelity is demonstrated to be 85%–95%. Future plans include further increasing the coherence time and number of qubits. This system can be a basis for hybrid quantum–classical optimization. Systems based on superconducting qubits are of interest for investigating Ising-type models, magnetic clusters, and adiabatic quantum simulation. Enabling technologies here include qubit fabrication, flip-chip, and multilayer architectures.

Neutral atoms and ions. Fundamental physics related to quantum information processing is to a large extent dealing with trapped cold atoms and/or ions. In this line of research, in contrast to superconducting qubits, the balance between fundamentals and applications is slightly shifted towards fundamental aspects. Possibilities for quantum computing and simulations, which are offered by neutral atoms and ions, are really unique. Several groups in Russia work towards obtaining atomic ensembles and systems of cold ions under reasonable levels of experimental control. The particular species being studied include Rb atoms, Tm atoms, and Li atoms, as well as Yb ions and Mg ions in Paul traps.

In particular, quantum computing systems based on neutral Rb atoms are under development in the framework of the project supported by the Foundation for Advanced Research. This collaborative project bringing together teams of QTC MSU and groups at Rzhanov Institute of Semiconductor Physics RAS (Novosibirsk) takes advantage of existing detailed knowledge of properties of cold Rb atoms and their applications in quantum information processing. The goal of the project is to demonstrate a platform for both universal quantum computation and quantum simulation with 50 qubits. The atomic quantum register under development is based on arrays of single Rb atoms in dipole microtraps cooled below 50 μK . Current experiments deal with arrays of up to 100 sites with individual addressing and dynamic rearrangement. An important milestone in this effort is to realize individual addressing and control of the qubits as well as quantum gates. Bringing together expertise in Rydberg atom physics and single atom trapping, the project aims at developing fast and high fidelity two-qubit gates and long coherence times for hyperfine qubits. An ultimate near-term goal is a fully programmable device which may be operated both as a digital computer and as an analog quantum simulator. Further steps and follow up projects may include scaling up rubidium registers up to $\sim 10^3$ sites in 3D trap arrays, as well as using other atomic species, especially alkaline-earth and rare-earth atoms.

Ongoing research on ultracold Tm atoms (RQC) and Li atoms (Institute of Applied Physics RAS, Nizhny Novgorod) are concentrated on obtaining ultracold gases in the degenerate regime. Tm atoms in an optical lattice can be considered as a promising platform for quantum simulation due to the presence of long-range dipole–dipole interparticle interaction. Moreover, a simple structure of levels and resonances makes such a system promising for quantum simulation of magnetic properties and phase transitions. Research activities with Tm atoms include loading of BEC of Tm atoms in optical lattices, creating multicomponent species, and simulating magnetic phenomena. Ultracold ensembles of fermionic Li atoms are of great interest due to the possibility to demonstrate a high degree of control of interparticle interaction, allowing, in particular, the realization of BEC–BSC crossover.

On the subject of quantum computing with ions, there is extensive ongoing research on loading, trapping, and laser control for Yb ions and Mg ions. These studies are primarily located at the P. N. Lebedev Physics Institute RAS and Institute of Laser Physics RAS (Siberian Branch). The goals for the next five years include the increase in the number of qubits that are used for computing (from 5 up to 50), coherence time up to seconds, and fidelity of one-qubit and two-qubit operations up to 99.99% and 99%, respectively.

Integrated photonics. Single photons are ideal carriers of quantum information and linear optical paradigm for quantum computation has many unique features, such as the virtual absence of decoherence in an ordinary sense. With the development of high-rate sources of indistinguishable single photons and highly efficient superconducting single-photon detectors, optical architecture for quantum computing becomes especially promising.

The realization of quantum information processing via integrated photonics is supported by the Foundation for Advanced Research and is a concerted effort of multiple groups. The envisioned architecture of the linear optical quantum computer will include semiconductor quantum dots based source of single photons developed by the Ioffe Physical-Technical Institute RAS and superconducting detectors from Russian-based company Scontel. Small-scale prototypes of universal programmable linear optical circuits are being developed at QTC MSU with the use of the femtosecond laser writing technique, while up-scaling the system will require larger chips based on silicon nitride waveguides contributed by nanofab at from Russian-based company ‘Terahertz and infrared photonics’ and Bauman Moscow State Technical University.

The crucial challenges in linear optical quantum computing in the longer term are reducing losses in integrated waveguides and integrating photon sources and detectors on a chip. Fortunately, there are groups in Russia with excellent expertise in both nanofabricated single-photon sources and in superconducting single-photon detectors, including their on-chip integration. Developing these technologies further may be one of the key future directions for the Russian nanophotonics community.

Polaritronics. Simulating complex systems is also possible with the use of ensembles of quasiparticles, such as excitons in solid-state systems and polaritons. In this field, Russia boasts an extensive and successful theoretical activity. Specifically, important contributions include research of long-lived excitons formed by spatially separated electrons and holes. This idea has pushed forward experimental and theoretical studies of coherent states of quasiparticles in solid-state systems.

Recently experimental realizing the classical XY Hamiltonian in polariton simulators have been demonstrated by groups at Skoltech. Within a systems containing 45 coupled polariton condensates, various magnetic phases, such as ferromagnetic, anti-ferromagnetic, and frustrated spin configurations on a linear chain, have been demonstrated. This system is under active development and allows realizing unconventional superfluids, spin liquids, Berezinskii–Kosterlitz–Thouless phase transition, and classical magnetism, among the many systems that are described by the XY Hamiltonian. Theoretical studies of many-body physics with polaritons are conducted at the RQC and Spin Optics Laboratory (St. Petersburg State University).

Next steps in the development of polariton simulators would include the scaling the system to 1000 and more coherently coupled condensates and the demonstration of a quantum simulator with an architecture similar to one of the existing quantum simulators based on superconducting qubits. For the latter task, qubits based on split-ring polariton condensates seem to be a promising platform.

Quantum materials research. In-silico design of novel knowledge-based quantum materials are one of the main goals of modern materials science. Russia has traditionally supported this field, and several projects have been carried out recent years. One can particularly note several research entities. Materials discovery laboratory at Skolkovo Institute of Science and Technology (Skoltech, Moscow), which is funded primary by Skolkovo Institute of Science and Technology and several Russian Industrial Companies. The basic instrument developed by the group, known as USPEX software (uspex-team.org), has over 5000 registered users. Among the latest results of Skoltech’s group are the discovery of novel helium compound Na_2He under pressure, prediction of high-temperature ($T_c = 241$ K) superconductor, and the discovery of a new hard/superhard material WB_5 . Modeling and Development of New Materials Laboratory at MISiS, Moscow (funded primary by Ministry of Science and Higher Education via Megagrant and 5-100 Programs). The MISiS group succeeded in studying the properties of materials under high pressure and phenomena in the iron compounds, including topological transitions in iron. The group at the Institute for Metal Physics RAS (Ekaterinburg), which is funded via the special grant of the RSF. This group has an expertise in magnetic, Mott-insulator and other correlated materials. The RQC Correlated Quantum Systems aims to describe strongly correlated materials with developed collective fluctuations, such as high- T_c cuprates. It resulted in the formulation of a new diagrammatic technique, so-called dual-variable method capable of accounting for strong long-range correlations.

Theory, algorithms, and software. Substantial contributions in the mathematical foundations of quantum theory, quantum statistics, and quantum information theory have been made by Prof A S Holevo. His outstanding results, in particular the famous Holevo’s theorem, are in the foundations of quantum information science. The field of mathematical theory of quantum channels and quantum information processing is under active development by Prof A S Holevo and his colleagues at the Steklov Mathematical Institute of Russian Academy of Sciences.

Research on quantum information processing in Russia also includes studies of ways to check quantum resources in NISQ devices by the group at the N. L. Dukhov All-Russia Institute of Science and Research, models for universal variational quantum computing at Skoltech’s Deep Quantum Laboratory, quantum information theory and quantum thermodynamics (together with collaborators from ETH Zürich and Argonne National Laboratory) research at the Moscow Institute of Physics and Technology, implementation of methods for the analysis and control for quantum systems by the group at the Valiev Institute of Physics and Technology RAS, and applications, in particular, in quantum machine learning. There is a number of proposals for architectures

for quantum computing and topologically-protected quantum information processing with ultracold particles by RQC theory groups.

Significant efforts are concentrated on studies of condensed matter theory, in particular, by the Laboratory for Condensed Matter Physics at National Research University Higher School of Economics. The laboratory joins leading researchers from Landau Institute for Theoretical Physics RAS, Kapitza Institute for Physics Problems RAS, Institute of Solid-State Physics RAS, Institute for Spectroscopy RAS, P. N. Lebedev Physical Institute RAS and etc. The focus of the laboratory is on low-temperature physics and nanophysics.

There is an ongoing research activity at the Skoltech's Laboratory for Quantum Information Processing. Founded in 2017, Skoltechs resident based theory effort, which is known as Deep Quantum Laboratory, specializes in the theory and experimental implementation of quantum enhanced algorithms for machine learning, quantum enhanced optimization and quantum enhanced simulation of electronic structure. The lab has developed a detailed professional education program covering modern quantum technology, as well as an MSc track in 'quantum information processing' held at the Skolkovo Institute of Science and Technology. The lab is known for its work on quantum algorithms, for several proofs in the area of Hamiltonian complexity theory and for many results on the theory of tensor network states. Ongoing work seeks to understand the full application scope of contemporary (noisy) quantum information processing devices.

Science-industry collaboration. An example of a project initiated by the industry is the Quantum Machine Learning Initiative under the umbrella of the RQC with an annual budget of 1.4 million EUR, which is supported by Gazprombank. There are several important directions: (i) research on quantum algorithms for universal quantum computers that could act as the building blocks of machine learning programs; (ii) research on programmable special-purpose machines that are not universal quantum computers yet possess some quantum properties and quantum-inspired algorithms that enhance training classical neural networks; (iii) using classical neural networks in order to obtain variational solutions for many-body quantum-mechanical problems. Research within this initiative has already produced an optimization algorithm based on simulating the coherent Ising machine and classical machine learning tool for revealing quantum chaos.

Quantum communications

In the field of quantum communications, the Russian Quantum Technologies Roadmap considers the following directions: point-to-point quantum key distribution; trusted-nodes-based quantum key distribution networks; untrusted-nodes-based quantum key distribution networks; free-space quantum key distribution for satellites and drones; quantum-safe (post-quantum) classical cryptography.

Practical, commercial quantum key distribution in both fiber and free-space channels is being pursued by three major developers: QTC MSU (together with Infotecs company), RQC (together with NTI Center for Quantum Communications at National University of Science and Technology MISiS and company QRate), and ITMO University (together with Quantum Communications company).

The group at the QTC MSU works on the development of quantum key distribution devices based on the original protocol with geometrically uniform states; the system has been tested on 32 km optical lines in urban conditions. In collaboration with its commercial partner—a Russian hardware security company Infotecs—the group has developed a full-scale commercial technology, including encryption units and encrypted messaging (video/voice/text) systems using quantum keys. The group from ITMO implements a subcarrier wave quantum key distribution system that has also been tested in urban conditions. The ITMO project and related spin-off company entitled as Quantum Communications are successful in attracting private investments. These systems have been developed in the framework of projects initiated by the Ministry of Science and Higher Education of the Russian Federation and projects of the Foundation for Advanced Research.

The development of the prototype of a commercial quantum communication device by the RQC and its spin-off company QRate in 2015–2017 has been supported by the Ministry of Science and Higher Education together with the industrial partnership of Gazprombank. The total budget of the project is ~6 million EUR. This investment resulted in a number of products that are being produced in Russia, such as an academic modular setup for R&D, industrial device, and single photon detectors. The post-processing algorithm developed in this project demonstrates performance that is superior to previously known analogs. In 2016–2018, the system developed by RQC and QRate has been tested in urban conditions. The tests included demonstrations for large Russian banks, such as Garprombank (integrated with S-Terra hardware encryption units) and Sberbank (integrated with Amicon hardware encryptors). QRate devices are suitable for various business applications, such as quantum-secured VPN, which has been demonstrated in Sberbank, and quantum-secured distributed ledgers.

In the period from December 2018 to March 2019, the largest Russian communication service provider PJSC Rostelecom has conducted testing existing Russian cryptographic solutions using quantum key

distribution devices of the three Russian vendors. Rostelecoms experts designed a fiber-optical link of the length of 58 km (with total about 18 dB) between the Moscow Rostelecom node M10 and laboratory at Skolkovo Institute of Science and Technology Devices for cryptographic protection, using quantum key distribution devices of the three Russian vendors, have demonstrated competitive results, which confirmed the functional applicability and the relevance of quantum technologies. PJSC Rostelecom has initiated a project for designing a multisite regional and backbone quantum key distribution networks, in particular, a quantum key distribution network from Moscow to Udomlya.

Russian laws require any cryptographic system to be domestically certified if it is used by the government or by commercial entities working on public contracts that require cryptographic information security. Commercial uses of cryptography that do not involve such public contracts are not regulated but nevertheless advised to comply with the same certification procedures. The next phase of the domestic quantum key distribution development is therefore standardization. The government body overseeing cryptography has been organizing a series of workshops roughly twice a year to track and coordinate this development with all domestic players and potential users of quantum key distribution.

An important part of the work on standardization is security testing commercial quantum key distribution systems. In this context, it is important to mention that Quantum Hacking Lab is a part of NTI Center for Quantum Communications at National University of Science and Technology MISiS.

A two-year R&D call for the development of domestic certification capabilities is upcoming, funded by the National Program Digital Economy. Also, the key Russian players are contributing to the development of international standards at ETSI and International Standards Organisation (ISO).

Quantum optics and quantum repeaters. In addition to practical quantum communication, there are a number of groups involved in basic research aimed at developing the tools of future large-scale quantum networks and quantum repeaters. This research can be classified into two domains. First, several groups pursue wide-profile experimental efforts on quantum-optical engineering and tomography with the vision of enhancing the technologies of synthesizing, manipulating and characterizing complex quantum states of the light field. A prominent example is the group at QTC MSU, which is developing reconfigurable photonics on a chip, quantum state engineering in the spatial domain, and adaptive Bayesian quantum tomography. Another group, at the RQC, specializes in ‘hybrid’ discrete-continuous approach to quantum-optical technology. Their most significant recent accomplishments include multimode quantum process tomography, distillation of continuous-variable entanglement, ‘breeding’ of Schrödinger cat states, and interconversion of qubits between discrete- and continuous- variable domains.

Second, there exist theoretical and experimental efforts to study the exchange of quantum information between light and matter for applications in quantum repeaters. Groups in St. Petersburg possess formidable expertise in Raman processes in alkali atoms and provide theoretical support to a number of international researchers. Thematically related studies in atomic physics are implemented by theoreticians groups in Novosibirsk; however the efforts of that group are aimed towards high-precision quantum metrology rather than communications. A group in St. Petersburg works a unique know-how in the fabrication of anti-relaxation coated atomic vapor cells, which enable extremely low decoherence rates and therefore are in high demand internationally.

Another promising venue for light-matter interfacing, in addition to atomic physics, is rare-earth doped crystals. The expertise in this domain is localized in Kazan. Several groups in Kazan, in particular the one at Kazan Quantum Center, work on the application of photon echoes to quantum-optical memory and developing new quantum memory protocols and applications.

Quantum metrology and sensing

Quantum metrology and sensing have not been fully covered by the programs of existing NTI centers on quantum technology. However, Russian researchers demonstrate international leadership in these fields, in particular, in optomechanics, color centers for magnetometry and nanothermometry, and quantum clocks. The following directions are listed in the Russian Quantum Technologies Roadmap: optical atomic clocks; gravimeters, accelerometers, and gyroscopes based on cold atoms; gyroscopes based on solid-state spin ensembles; local sensors on temperature and electromagnetic fields based on color centers; magnetic sensors based on coherent spin states in magneto-ordered structures; plasmonic biosensors; solid-state photodetectors; trace gas detection based on double optical frequency combs.

Quantum clocks. Important results have been achieved in the field of quantum clocks. The existing project is aimed on the development of a compact (1 m^3) frequency standard device based on a single Yb^+ ion. The work joining P N Lebedev Physical Institute RAS, Skolkovo Institute of Science and Technology, Institute of Laser Physics RAS (Siberian Branch), Avesta Company, and Russian Space Systems Company is aimed on the future

use of the device for GLONASS. These projects (in particular, the Federal Project GLONASS, 2012–2020) is supported by Ministry of Science and Higher Education.

Photodetectors for quantum light. The research on optical quantum metrology in Russia may be traced back to pioneering works of Prof D N Klyshko on quantum photometry and absolute calibration of photodetectors with non-classical light. Nowadays, photon correlations in spontaneous parametric down conversion are utilized for practical applications including quantum imaging and lithography, spectroscopy, quantum optical coherence tomography, and other applications. Interestingly, fundamental research in spectroscopy with SPDC light led recently to practical technique, enabling spectroscopy in the far infrared with visible photodetectors and cameras. The extension of this technique further into the THz range is possible in the nearest future.

Color centers. Development of high-resolution temperature measurement techniques made it possible to question temperature function at the single-cell level, or even within the cell. Quantum sensing techniques for high-resolution, all-optical thermometry and magnetometry are under active development by a cross-disciplinary collaboration that joins RQC, Physics Department and International Laser Center, M. V. Lomonosov Moscow State University, Department of Physics and Astronomy, Texas A&M University (USA) P. N. Lebedev Physical Institute RAS, B. I. Stepanov Institute of Physics, National Academy of Science of Belarus (Belarus), Kazan Quantum Center, A. N. Tupolev Kazan Technical University, Moscow Physicotechnical Institute, Russia, and Institute of Bio-organic Chemistry RAS. This work is supported by the Megagrant program from the Ministry of Science of Russian Federation and several grants from the RFBR.

A nitrogen-vacancy (NV) color center in diamond is a unique solid-state quantum system, where the electron spin can be manipulated, polarized, and read out at room temperature using electromagnetic fields. Due to their remarkable electron-spin properties, NV centers offer much promise as solid-state qubits, single-photon sources, efficient contrast agents for superresolution optical microscopy, quantum sensors for nanoscale thermometry of living cells, and photostable, nonbleaching markers for bioimaging. The sensitivity of the electron spin in an NV center to an external magnetic field has been recently shown to enable a new approach in magnetometry, allowing weak magnetic fields to be detected and imaged with an unprecedented spatial resolution and a remarkable sensitivity.

One of the key idea of the project is that integrating NV diamond photonics with advanced fiber-optic technologies provides a versatile fiber-optic platform for quantum sensing, offering unique solutions for optical magnetometry, biophotonics, and neuroscience. Such a fiber probe integrated with an NV-diamond quantum sensor and a microwave transmission line allows a high-sensitivity, high-speed imaging of magnetic fields and offers a unique tool for a thermometry of individual biological cells in *in vivo* experiments.

Recent advances in optical magnetometry pave the way toward unprecedented spatial resolution and remarkably high sensitivity in magnetic field detection, offering unique tools for the measurement of weak magnetic fields in a broad variety of areas from astrophysics, geosciences, and the physics of fundamental symmetries to medicine and life sciences. To unleash the full potential of this emerging technology and make it compatible with the requirements of practical quantum technologies and *in vivo* studies in life sciences, optical magnetometers have to be integrated with fiber-optic probes. Specifically, a scanned fiber-optic probe for magnetic-field imaging, where NV centers are coupled to an optical fiber integrated with a two-wire microwave transmission line, has been demonstrated. Integration of a microwave transmission line with an optical fiber and a diamond quantum thermometer has been shown to allow thermogenetic single-cell activation to be combined with accurate local online temperature measurements based on an optical detection of electron spin resonance in NV centers in diamond.

Quantum sensors based on advanced quantum materials. Novel materials based on quantum materials (such as graphene, topological insulators, van der Waals heterostructures, and others) are of great interest for biomedical applications and Internet of Things. This direction is being developed in several groups in Russia, including Laboratory of Nanooptics and Plasmonics, Center for Photonics and 2D Materials at the Moscow Institute of Physics and Technology, and science industry collaborations, such as collaboration between Samsung Advanced Institute of Technology and group at the Institute of Spectroscopy RAS.

Optomechanics. The history of quantum optomechanics in Russia can be traced back to the late 1960s—early 1970s when the first attempts to detect gravitational waves from astrophysical sources were made. These detectors were based on solid-state resonant bars which converted gravitational wave strain into the bars' mechanical excitation. Unfortunately, despite the very high sensitivity shown by these devices (about $\sim 10^{-16}$ m in terms of mechanical elongation), they failed to detect gravitational waves.

This negative result triggered the search of new quantum methods of measurements of small displacements and forces. The research group at the Moscow State University, headed by prof V B Braginsky, from the very beginning was one of the major contributors in this research, introducing, in particular, the key concepts of the Standard Quantum Limit (SQL) and the Quantum Non-Demolition measurement. In 1990s it joined the LIGO Scientific Collaboration, the international organization aimed at development of the new laser interferometric generation of gravitational wave detectors, as 'the Moscow group'.

Currently, the Moscow group continues to be one of the key participants in the development of quantum measurements schemes for the gravitational wave detectors (see e.g.). A part of this activity takes place at the RQC Quantum optomechanics group. This research was supported by various grants by the RFBR, the recurring series of NSF grants ‘Low noise suspensions and readout systems for LIGO’ (1995–2016) and the RSF’s grant ‘Physical principles of gravitational wave detectors of 3-d generation’ (2017–2019). The group is planning to continue the development of optomechanical schemes with sub-SQL sensitivity. In particular, as the first step, hybrid schemes which use additional atomic spin ensembles (developed with the participation of a group at St. Petersburg State University) will be explored and the practical configurations of the quantum speedometer scheme will be developed. Applications of these schemes are not limited to laser gravitational wave detectors. Further application areas include atomic force microscopes and optomechanical quantum memory devices.

Conclusion

Russia builds on a long tradition of quantum science and technology and is currently hosting an established, vibrant, collaborative and growing effort dedicated to quantum science and technologies. As we have described, the current quantum landscape of the Russian Federation covers a wide range of experimental platforms being built for quantum enhanced computation, quantum enhanced simulation, quantum secure communication and quantum enhanced metrology. The recent NTI programs and Digital Economy National Program provide substantial funding and encourage the construction of cohesive research bonds among various national entities. A crucial ingredient of a successful program in quantum technologies is an efficient balance between fundamental science and technological aspects. Intense global interest, broadband domestic expertise and substantial financial support from the government and industry position quantum science and technology in the Russian Federation for dramatic growth over the next five years.

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