Unveiling the potential of phonons and photons in quantum computing and communication

Marat Nuriev[1*], *Rimma* Zaripova[2], and *Saidmagomed* Alikhadzhiev[3]

[1]Kazan National Research Technical University named after A. N. Tupolev – KAI, Kazan, Russia
[2]Kazan State Power Engineering University, Kazan, Russia
[3]Kadyrov Chechen State University, Grozny, Russia

Abstract. This article explores the cutting-edge advancements in quantum technologies, focusing on the innovative use of atomic interactions and the role of phonons and photons in quantum systems. We delve into the recent discovery by researchers at the University of Washington, who have demonstrated the potential of atomic vibrations for tracking and transmitting quantum information, laying the groundwork for new communication systems, high-precision sensors, and powerful computational architectures. The discussion extends to the domain of optomechanics, where light and mechanical vibrations are intricately linked, offering new quantum phenomena for controlling single photons through integrated optical circuits. The study of excitons and their interaction with photons highlights the crucial role these quasi-particles play in the absorption and emission of light in semiconductors, and their potential for encoding and transmitting quantum information. Furthermore, the article addresses the challenges and solutions in leveraging phonons within quantum technologies, emphasizing their application in quantum computing, communication, and sensing. The inherent challenges of simulating quantum systems on classical computers are also discussed, alongside the pivotal role of software simulations in quantum algorithm development, education, and research. In conclusion, the article underscores the ongoing journey of quantum technology development, marked by significant challenges but driven by the immense potential to revolutionize computing, communication, and sensing. The integration of quantum principles into practical applications continues to push the boundaries of what is technologically feasible, heralding a new era of innovation and discovery in the quantum realm.

1 Introduction

In recent years, there has been a significant surge in interest towards quantum technologies, particularly in the realm of quantum computing. The allure of quantum computers lies in their vastly superior computational capabilities when compared to traditional computing systems. A pivotal aspect of quantum computing involves the transmission and storage of quantum information. Furthermore, given the complex, multi-faceted nature of the problems addressed within these systems, coupled with their inherent ambiguity, there emerges a pressing need

* Corresponding author: marat_nu1@mail.ru

for the development of efficient methodologies to tackle these challenges. This paper presents the findings of a research endeavor dedicated to exploring the potential of utilizing atomic vibrations for the monitoring and transmission of quantum information.

Researchers from the University of Washington have unearthed the potential to track atomic vibrations, or the mechanical oscillations between two arrays of atoms, utilizing a laser that prompts the atoms to emit light. This phenomenon can be harnessed to record and transmit quantum information.

The device developed from this research holds the promise to serve as the cornerstone for novel communication systems, high-precision sensors, and potent computing architectures. This breakthrough stands to catalyze a quantum revolution, heralding an era of faster, more accurate data processing, alongside secure and reliable communication networks.

The research findings were published on June 1, 2023, by the University of Washington, marking a significant milestone in the advancement of quantum technologies [1-3]. This development not only underscores the intricate interplay between atomic interactions and quantum information dynamics but also paves the way for groundbreaking applications in various sectors, including cybersecurity, material science, and beyond, thereby setting the stage for the next leap in quantum technological evolution.

2 Description and features of the subject area

This innovative atomic-scale platform, grounded in what the scientific community refers to as "optomechanics," intertwines light with mechanical vibrations in a seamless manner, explains a senior professor specializing in electrical engineering, computational technology, and physics. This integration heralds a new breed of quantum phenomena that could be instrumental in controlling individual photons traversing through integrated optical circuits, opening up a plethora of applications [4,5].

Previously, the team delved into a quantum-scale quasi-particle known as the "exciton." This system of quasi-particles, which can manifest as electrons, phonons, magnons, among others, presents a fascinating field of study. Excitons and photons represent two distinct particle types, with excitons possessing specific energy and momentum, enabling their movement across crystals [6]. In contrast, photons – the particles of light – carry energy and momentum but are massless, allowing them to travel at the speed of light. Excitons play a crucial role in the absorption and emission processes of light in semiconductors, while photons are pivotal in long-distance information transmission. Each quasi-particle is characterized by its energy, momentum, and mass, interacting with one another under the principles of quantum mechanics. Information can be encoded within an exciton and subsequently retrieved as a photon, the smallest energy unit considered a quantum of light. Photon properties, such as polarization, wavelength, and emission timing, can serve as a quantum bit of information, or "qubit," for quantum computing and communication processes. Since this "qubit" is carried by a photon, it moves at light speed [7,8].

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Fig. 1. Visual representation of a quantum of light.

From a broader perspective, this research underscores the necessity for reliable methods to create, process, store, and transmit quantum bits of information (qubits) for constructing a quantum network [9]. "Photons are the most suitable candidates for transferring quantum information over long distances, as optical fibers facilitate high-speed photon transmission with minimal energy or information loss," states the lead author of the study.

The researchers engaged with excitons to develop a single-photon emitter, or "quantum emitter," crucial for quantum technologies related to light and optics. They achieved this by stacking two thin layers of tungsten and selenium atoms, known as tungsten diselenide, atop each other [10,11].

When a specific laser pulse was applied, it knocked an electron out of a tungsten diselenide atom, creating an exciton. Each exciton consists of a negatively charged electron in one material layer and a positively charged "hole" in another layer, where the missing electron was. Due to the mutual attraction of charges, the electron and "hole" within each exciton are tightly bound. Eventually, as the electron drops back into its original "hole," the exciton releases a photon carrying quantum information, thus realizing the quantum light source envisioned by the team [12].

Furthermore, the team discovered that tungsten diselenide atoms emit another type of quasi-particle, known as phonons. These phonons result from atomic vibrations akin to breathing. In this scenario, the two layers of tungsten diselenide atoms act as tiny membranes, vibrating relative to each other and creating phonons. This marks the first observation of such phonons in a single-photon source within a two-dimensional atomic system of this kind.

3 Challenges and solutions

When scientists measured the light emission spectrum, they encountered several identical peaks, a discovery that hinted at the intricate interactions within quantum systems. Each phonon emitted by an exciton was found to be entangled with one or more other phonons, akin to ascending the quantum energy ladder one step at a time. These energy transitions were represented as equidistant peaks on the spectrum, illustrating the quantized nature of energy in these interactions [13,14].

Data security and protection pose significant challenges in distributed and multi-cloud environments, as systems must be safeguarded against external threats and internal vulnerabilities [15]. Furthermore, maintaining high performance levels while scaling, especially in global applications dealing with vast data volumes, presents a complex problem.

A phonon is a quasi-particle, a quantum of energy associated with the coordinated vibrational movement of atoms in a solid's ideal crystal lattice. Conceptualizing lattice vibrations as a collection of phonons proves to be a convenient approach for analyzing the interactions between electrons, light quanta, and other particles, whose momentum may be transferred to the lattice [16,17].

According to the principle of wave-particle duality, any object can be perceived as both a wave and a particle (or quasi-particle) [18]. For instance, light can be interpreted as a collection of electromagnetic waves or as a stream of photons, which travel at the speed of light in a vacuum.

Figure 2 illustrates the collective nature of electromagnetic waves, where the wave amplitude and flux density correspond in a manner that ensures consistency in spectral power density across both interpretations. In quantum mechanics, the concept of duality is applied to elementary particles, including electrons [19,20].

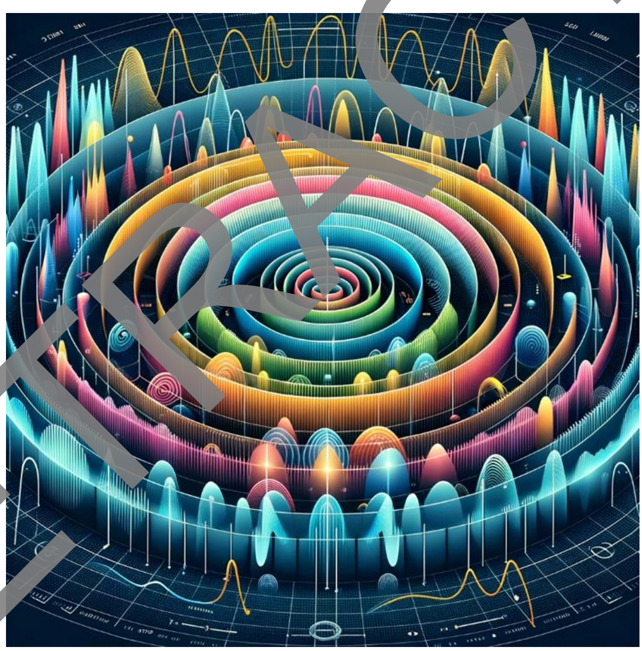

Fig. 2. A collection of electromagnetic waves.

Similarly, elastic waves (narrowly defined as sound) can be perceived as a stream of quasi-particles called phonons. Thus, the state of a crystal lattice can be considered as a gas of phononic quasi-particles, analogous to more familiar electron or photon gases [21,22].

Scientists have become intrigued by the potential of employing phonons in quantum technologies [23,24]. By applying an electrical voltage, they discovered that the energy of interaction between linked phonons and emitted photons could be altered. They were able to measure and control these changes, opening new avenues for manipulating quantum states and enhancing the efficiency of quantum devices [25].

This exploration into phonon-photon interactions marks a significant step forward in quantum research, suggesting new methods for quantum information processing and storage. By harnessing these interactions, researchers aim to develop more sophisticated quantum systems, potentially revolutionizing our approach to computing, sensing, and communication in the quantum era [26,27].

4 Utilizing phonons in quantum technologies

The exploration of phonons in quantum technologies represents a cutting-edge frontier in the field of quantum mechanics and materials science. Phonons, the quanta of lattice vibrations within a material, are not merely byproducts of atomic movements but are fundamental to understanding and manipulating the material's thermal and electronic properties. Their integration into quantum technologies opens up new avenues for information processing, communication, and sensing, leveraging the unique interactions between phonons and other quantum particles such as photons and electrons [28].

Phonons act as quantum messengers within materials, facilitating energy transfer and mediating interactions between particles. In quantum technologies, phonons can be harnessed to carry information, similar to the role photons play in optical systems. However, unlike photons, phonons are confined to the medium they propagate through, offering a different set of advantages and challenges for quantum communication and computation [29,30].

In quantum computing, phonons offer a novel approach to representing and manipulating quantum bits (qubits). Phononic systems can be engineered to create specific vibrational modes that interact in quantized ways, analogous to the energy levels in atoms. These interactions can be precisely controlled to perform quantum logic operations, offering a pathway to scalable and robust quantum computers [31]. The localized nature of phonons allows for high-density qubit arrays, potentially overcoming some of the scalability challenges faced by other quantum computing platforms.

Phonons can also play a pivotal role in quantum communication within solid-state systems. By enabling the transfer of quantum states through vibrational energy, phonons can facilitate entanglement and state transfer between distant qubits within a material. This capability is crucial for building quantum networks and long-range entangled systems, which are the backbone of quantum communication and distributed quantum computing [32,33].

The sensitivity of phonons to their environment makes them excellent candidates for quantum sensors. Phononic sensors can detect minute changes in temperature, pressure, and electromagnetic fields, translating these into measurable quantum states. This sensitivity, combined with the quantum nature of phonons, allows for precision measurements beyond the limits of classical sensing technologies, with applications ranging from fundamental physics research to practical environmental monitoring [34].

Despite the promising prospects, the utilization of phonons in quantum technologies is not without its challenges. Controlling and measuring phononic states with high precision requires sophisticated techniques and materials engineering. Additionally, phonons are inherently tied to the thermal state of the material, making them susceptible to decoherence and noise at higher temperatures [35,36]. Overcoming these challenges necessitates advances in materials science, quantum control techniques, and theoretical understanding of phonon-based systems.

The integration of phonons into quantum technologies represents a paradigm shift in how information and energy are manipulated at the quantum level. By tapping into the unique properties of phonons, researchers are uncovering new possibilities for quantum computing, communication, and sensing. As the field progresses, phonons may well become as fundamental to quantum technologies as photons have been to classical and quantum optics, heralding a new era of quantum innovation [37,38].

5 Software simulation of quantum computing

Software simulation of quantum computing stands as a pivotal intermediary between the theoretical underpinnings of quantum mechanics and the practical applications of quantum computing. Given the complexity, cost, and limited availability of physical quantum computers, software simulations emerge as an essential tool for researchers, developers, and educators [39]. They facilitate the exploration of quantum algorithms, the testing of quantum circuits, and the comprehension of quantum phenomena, all without the necessity of physical quantum hardware [41,42].

Quantum simulators, which are software tools designed to emulate the behavior of quantum systems using classical computing resources, play a crucial role in this domain. These simulators allow for the virtual execution of quantum operations, measurements, and the creation of entanglement, thereby serving as instrumental platforms for the design and validation of quantum algorithms. They provide valuable insights into the algorithms' functionality, efficiency, and potential limitations [43].

The software used for quantum simulation typically incorporates capabilities for the design and modification of quantum circuits, both visually and programmatically. It offers representations of quantum states, including superposition and entanglement, and features a comprehensive library of quantum gates for use on qubits within the simulated circuits. Moreover, these simulators include tools for measuring qubits and analyzing outcomes, as well as for modeling real-world quantum noise and errors to assess their impact on quantum computations [44,45].

However, simulating quantum systems on classical computers presents significant challenges, primarily due to the exponential growth of quantum states with each added qubit. This exponential growth demands resources that scale similarly, thereby constraining the size of quantum systems that can be feasibly simulated [46]. To address these challenges, researchers are developing advanced techniques, such as tensor network methods and quantum circuit cutting, which aim to simulate larger quantum systems more efficiently.

The application of quantum simulation spans various areas, including the development and testing of quantum algorithms, educational purposes for facilitating learning about quantum computing, and research and development for exploring quantum computing's theoretical foundations and its potential for solving complex problems in diverse fields [47,48].

The evolution of quantum simulation software is closely linked to advances in classical computing hardware, parallel computing, and machine learning. The integration of quantum simulation with high-performance computing and cloud services has broadened access to quantum simulations and reduced computational barriers. Furthermore, machine learning techniques are being increasingly employed to enhance the efficiency of quantum simulations, predict outcomes, and even aid in the design of new quantum algorithms.

The role of software simulation in quantum computing is multifaceted, contributing significantly to the development, understanding, and dissemination of quantum computing technologies. As the quantum computing field progresses, the capabilities and applications of quantum simulators are expected to grow, driving innovation in quantum algorithms and fostering a wider comprehension and adoption of quantum computing principles [49,50]

6 Conclusion

In conclusion, this article has delved into the emerging frontier of quantum technologies, highlighting the significant advancements and the challenges that accompany them. From the novel use of atomic vibrations for information transmission to the intricate dance of photons and phonons in quantum systems, we stand on the cusp of a technological revolution that promises to redefine our understanding of computation, communication, and sensing.

The exploration of optomechanics and the harnessing of exciton and phonon interactions have unveiled new possibilities for quantum computing and quantum communication systems. These advancements not only enhance our capability to process and transmit information with unprecedented efficiency but also open new avenues for high-precision sensing technologies.

Software simulations of quantum computing have emerged as indispensable tools, enabling researchers, developers, and educators to explore the vast potential of quantum algorithms and circuits in a virtual environment. Despite the inherent challenges posed by the simulation of quantum systems on classical hardware, ongoing developments in computational techniques and machine learning are paving the way for more efficient and accessible quantum simulations.

As we navigate through these developments, the interplay between theoretical research and practical applications continues to drive the field forward, bringing us closer to realizing the full potential of quantum technologies. The integration of quantum principles into computing and communication systems is not without its challenges, including issues of scalability, coherence, and error correction. Yet, the progress made thus far signals a promising trajectory towards overcoming these hurdles and unlocking new capabilities that were once considered beyond reach.

The journey of quantum technology development is a testament to the power of human curiosity and ingenuity. As we continue to unravel the mysteries of the quantum world, we edge closer to a future where quantum technologies are integral to our everyday lives, offering solutions to some of the most complex problems in computing, communication, and beyond. The path ahead is fraught with challenges, but the potential rewards make this endeavor not only worthwhile but essential for the next leap in our technological evolution.

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