jet INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2026, VOL. 72, NO. 1, PP. 1-7
Manuscript received January 14, 2026; revised January, 2026. doi: 10.24425/ijet.2026.157899

Influence of IQT on research in ICT part 7

Aleksander B. Mazur, Safiya Aliaksandrava, Piotr P. Jeżak, Piotr A. Fokow, Szymon S. Tokarski, and Ryszard S.Romaniuk

***Abstract*—The advanced Quantum Information Technologies subject for Ph.D. students in Electronics Engineering and ICT consists of three parts. A few review lectures concentrate on topics which may be of interest for the students due to their fields of research done individually in their theses. The lectures indicate the diversity of the QIT field, resting on physics and applied mathematics, but possessing wide application range in quantum computing, communications and metrology. The individual IQT seminars prepared by Ph.D. students are as closely related to their real theses as possible. Important part of the seminar is a discussion among the students. The task was to enrich, possibly with a quantum layer, the current research efforts in ICT. And to imagine, what value such a quantum enrichment adds to the research. The result is sometimes astonishing, especially in such cases when quantum layer may be functionally deeply embedded. The final part was to write a short paragraph to a common paper related to individual quantum layer addition to the own research. The paper presents some results of such experiment and is a continuation of previous papers of the same style.**

***Keywords*—quantum information technology; QIT; teaching of QIT; Ph.D. students view on QIT; QIT implementation in ICT theses**

I. INTRODUCTION

ADVANCED lecture for a group of diverse Ph.D. students is a demanding task. They are strongly concentrated on their individual research efforts. Timing of their Ph.D. study is demanding and they try to omit things which do not help them to go forward with the research. The subject on the Quantum Information Technology is designed in this way as not to slow down their work but to help and perhaps shed a new light on their research from a completely different yet very modern and promising perspective, the quantum one. The quantum perspective, especially when used against your serious personal research effort, is really very useful in the most of cases. Quantum integrated circuits are natural extensions of photonic integrated circuits. Quantum methods are used in simulations of large high energy experiments. Quantum simulators and annealers are used for research on molecular dynamics in material engineering and technology. IQT is used in a number of security solutions. A lot of photonic crystal technologies may be extended into quantum level. Quantum sensors include also a new generation of ionizing radiation devices and systems. Quantum dot dynamics is used in cancer diagnostics and therapy. IQT is used in automobiles and in aeronautics. Artificial Neural Network are extended successfully to quantum version. Power engineering start to adapt some quantum methods. IQT promise for faster and more precise genome sequencing and data analysis. Smart quantum antennas may enter into operation in G6 technology. Quantum batteries combine new materials and start to use quantum supercapacitors. IQT will be indispensable in banking and other security solutions. the era of advanced technology, healthcare providers are increasingly exploring the potential of digital health solutions for remote patient monitoring and treatment using Internet-connected sensors and medical devices. Wireless Body Area Network (WBAN) serves as a critical enabler of remote health monitoring by providing cost-effective and efficient real-time solutions.

II. SCALABLE STRUCTURED SINGLE PHOTONS SOURCES

Structuring light involves controlling its many degrees of freedom (DoFs), such as polarization, orbital angular momentum (OAM), spatial modes, frequency, or pulse duration time. These degrees of freedom also translate to the level of individual photons, enabling the creation of high-dimensional quantum states, called qudits (d>2), as opposed to qubits (d=2). Two orthogonal polarization states of photon create two-dimensional Hilbert space and photon state can be described by Bloch sphere or equivalently Poincare sphere with basis states $|L\rangle, |R\rangle$. The values of the OAM of a photon form an orthonormal basis that is unlimited, unlike two-dimensional polarization-based states. Photon can carry OAM values $l\hbar$ in range $\dots, l-2, l-1, l, l+1, l+2 \dots$. where l is topological charge integer. Possible choice of structuring photons is using spatial modes e.g. Laguerre-Gauss modes that also form orthonormal basis and carry OAM or Hermite-Gauss mode family.

The generation of high-dimensional quantum states is desirable for applications in quantum cryptography, quantum imaging, and quantum sensors. High-dimensional states carry more quantum information per photon what is promising in quantum communications and computing applications. Classic structured beams exhibit also many other interesting properties such as non-diffraction and self-healing (e.g. Bessel beams, Airy beams). These properties also carry over to the level of single photons [1]. Bessel photons or Airy photons are generated with simultaneous confirmation of entanglement using Bell inequality tests [1,2]. Structured single photons also open the possibility of using many different degrees of freedom simultaneously, creating hyperentangled states or hybrid states.

The basic tool for generating single photons is spontaneous parametric down-conversion (SPDC), which has the advantage of producing an entangled biphoton state. Single-photon source

The authors are Ph.D.Students at Warsaw University of Technology, Poland (corresponding author e-mail: aleksander.mazur.dokt@pw.edu.pl).

Authors of successive chapters are: II – A.B.M., III – S.A., IV – P.P.J., V – P.A.F., VI – S.S.T.

quality is described with second order correlation function at zero delay $g^2(\tau = 0)$ which can be found by performing Hanbury-Brown-Twiss experiment. Ideal single photon source emits one photon at a time, so $g^2(\tau = 0)$ ideally is equal to 0. SPDC cannot produce single photons on demand but offers high levels of photon-antibunching in room temperature. Deterministic single-photon emitters are color centers, quantum dots or trapped atoms, but they have disadvantages e.g. operating at low temperatures and lack of replicability in fabrication process. Ideal single-photon source emits photons on-demand with identical properties, is scalable and emitted photons are in telecommunication spectral range to prevent losses in optical fiber transmission. Real world applications require also deterministic fabrication process and room-temperature working conditions.

The structuring of generated photons mainly involves bulk optical elements based on light spin-orbit coupling like spatial light modulators (SLMs) or q-plates that utilize geometric phase of light. Q-plates are liquid crystal (LC) devices with non-uniform orientation of LC molecules. Circularly polarized light passing through a q-plate gains orbital angular momentum and changes its polarization state to the opposite helicity. Q-plate action on the circularly polarized single photon state can be described as $|L\rangle \rightarrow |R\rangle\,|l = 2q\rangle$ and $|R\rangle \rightarrow |L\rangle|l = -2q\rangle$ where q is the q-plate topological charge. Combining q-plates with single photons source can generalate entangled states between polarization and OAM in form $|\psi\rangle = \cos\left(\frac{\phi}{2}\right)|l, R\rangle + \sin\left(\frac{\phi}{2}\right)|l + 2q, L\rangle$ for input right-handed circular polarization and input OAM l and $|\psi\rangle = \cos\left(\frac{\phi}{2}\right)|l, L\rangle + \sin\left(\frac{\phi}{2}\right)|l - 2q, R\rangle$ for input left-handed circular polarization and input OAM l. The main disadvantage of bulky SPDC source systems with external phase modulators is photon losses. Increase in quantum information per photon, by using high-dimensional states has no advantage over two-dimensional states in lossy environment. Despite theoretical advantages of high-dimensional states, they require precise handling and generation methods due to their lower resistance to noise and disturbances. High-dimensional states also require more projective measurements in quantum tomography process which scales like $O(d^2)$ with d dimensions. Because of that, different approaches to measurement process or obtaining entanglement witness are interesting direction of development.

For observing advantages of structured single photons in applications like quantum communication, metrology or quantum computing, reliable and deterministic sources are crucial. Promising direction of technology development would be combining high-quality on demand single-photon sources with novel methods of light structuring. The other possible choices are on-chip or fiber integrated structured single-photon sources. Propagation of OAM photon states is not possible in regular single-mode fibers, therefore there's a need for different fiber types, like ring-core fibers that guide OAM modes. Generating OAM biphotons in ring-core fibers with spontaneous four-wave mixing process has been presented [3]. Four-wave mixing process allows near-arbitrary spectral ranges of photon pairs. Solid-state sources for single photons with OAM have been demonstrated, but they require low operating temperatures (30 K) [4]. Very recently room-temperature OAM-SAM entangled source have been demonstrated that utilizes nanodiamonds with individual nitrogen-vacancy centers [5]. Every nitrogen-vacancy center has different properties as a single photon emitter, therefore there is a need of preselection of a ND-NV with desired characteristics. Structurization is obtained by Archimedean spiral grating made of hydrogen silsesquioxane and generated photons are SAM and OAM superposition states. Measured $g^2(0) = 0.16$ that indicates high single photon purity [5]. An interesting direction for combining the process of generating single photons with their structuring could be the use of liquid crystals (LC). Recently obtaining SPDC process in ferroelectric nematic liquid crystals (FNLC) has been presented [6]. FNLC have large dielectric constant that leads to high optical nonlinearity. Generated photons are entangled and molecular orientation twist controls polarization state of generated photons. Rate of generation process depends linearly on the pump power [6].

Considering the use of liquid crystals in the structuring process, this opens up the possibility of a single structured photons source in entirely liquid crystal form. That approach could potentially make quantum emitter compact and scalable, but photon generation is not on demand, due to SPDC process. LCs can be integrated with photonic crystal fibers (PCF) that could provide the opportunity of optical fiber integration. Integrating LCs with quantum dots could be possible choice in create deterministic sources with structuring possibilities. Lately there has been a work published on the change of the properties of ferroelectric liquid crystals by doping it with quantum dots [7]. From the point of view of deterministic source of structured photons that use liquid crystals doped with quantum dots, this would be a problematic effect. Work [8] shows different approach, using elliptical Bragg grating with quantum dot at the center, to obtain bright source of linearly polarized single photons. Source's characterization has been performed at cryogenic temperatures (4 K) [8]. Designing and creating scalable, deterministic source of structured single photons is still at development phase. Many approaches are possible; utilizing optical properties of ferroelectric liquid crystals, testing other nonlinear effects that generate single photons that allow optical fiber integration or designing nanostructures combined with quantum dots that emit photons with telecommunication wavelengths and operate at room temperatures.

III. TRAPPING AND COOLING OF CHARGED AND NEUTRAL PARTICLES IN QUANTUM EXPERIMENTS

Contemporary quantum science extends across numerous research domains, including quantum information processing, quantum metrology, biomedical applications, and precision studies of antimatter. Advancements in these areas increasingly depend on the capability to prepare, isolate, and manipulate well-defined quantum systems, from single atoms and ions to neutral and ultracold molecules. Such systems are intrinsically vulnerable to environmental perturbations. Thermal motion, fluctuating electro-magnetic fields, uncontrolled interactions with surrounding degrees of freedom rapidly degrade coherence and can severely limit the fidelity of quantum operations or the accuracy of high-precision measurements.

To reduce the influence of these effects, certain cooling and trapping methods have become important in modern quantum technologies. Trapping systems that use electromagnetic fields, optical dipole forces, or combinations of different field configurations make it possible to hold particles in a fixed region of space for long periods while limiting unwanted interactions with the surroundings. Cooling techniques work alongside these traps by lowering the particle's kinetic energy to extremely low temperatures of the order of sub-kelvins, where quantum effects determine their motion [9]. Combination of trapping and cooling techniques allows researchers to achieve the precise control needed for coherent manipulation of quantum states, high-resolution spectroscopy, and accurate tests of fundamental physical laws that underpin quantum technologies today. These points emphasize the central principle of particle confinement and cooling techniques depending strongly on the type of physical system in atomic, molecular and optical (AMO) quantum technologies.

Different platforms require specific methods to achieve stable confinement and low enough temperatures to allow reliable operations. Examining how these techniques are applied in each system is therefore essential for understanding their efficiency, scalability, and preparation of the systems. Trapped ions constitute one of the most promising platforms for quantum computing due to the relative ease of confinement and cooling of charged particles compared to neutral atoms. The implementation of two-qubit gates requires a collective motional degree of freedom. To have full control and precise quantum gates, these motional degrees of freedom must be cooled near their quantum ground state. Starting from free moving ions at room temperature, they are first confined within a Paul trap, which uses rapidly oscillating quadrupole electric field for radial confinement and direct-current end-cup electrodes for axial one [10]. In a Paul trap, ions are initially not cold. Their thermal motion corresponds to the room temperature, which results in an average motional occupation of approximately 10^6 quanta.

By applying Doppler cooling, it is possible to reduce the ion temperature from 300K to around 0.5mK, thereby lowering the average occupation of the collective motional modes to approximately 10 quanta. This fundamental cooling mechanism relies on the scattering force. In the simplified case of a two-level atomic system interacting with light, this force originates from the absorption and subsequent spontaneous emission of photons from a red-detuned laser. However, the ion temperature can be further reduced using a technique known as electromagnetically induced transparency (EIT) cooling, which enables cooling below the Doppler limit by selectively addressing motional sidebands. This technique relies on quantum interference in three-level systems to create a dark quantum state that is effectively decoupled from excitation. The laser selectively drives sideband transitions while suppressing carrier excitations, removing motional quanta and cooling the ions near their motional ground state. In contrast, neutral-atom qubits operate under a fundamentally different mechanism. Two-qubit gates in neutral atom systems are realized through the Rydberg blockade mechanism, in which the excitation of a control atom to a high-lying Rydberg state generates strong long-range interactions that inhibit the excitation of nearby target atoms. In a Zeeman slower, a spatially varying magnetic field compensates for the changing Doppler shift of decelerated atoms, keeping them resonant with a counter-propagating laser beam. Continuous absorption of photons provides a net opposing radiation-pressure force, reducing the atomic velocity from 300K to approximately 10K. After leaving the slower, the atoms are captured in a magneto-optical trap (MOT), where they are confined by restoring force [11]. In the nest stage, atoms are typically cooled via Doppler cooling technique to the Doppler limit and then trapped by optical tweezers. The trap is created by the gradient force of the laser, that pulls the particle toward the region of highest intensity. In addition, a scattering force pushes the particle along the laser propagation direction. Optical tweezers can tightly confine neutral species with trap frequencies up to approximately 1 MHz. Once particles are confined in optical tweezers, Raman sideband cooling is used to further reduce their motional energy. As a result, the atom held in each tweezer reaches three-dimensional ground state. Consequently, the application of the trapping and cooling techniques described above for both ions and neutral atoms provide the important conditions for high-fidelity quantum-gate operations and enable the practical implementation of quantum algorithms.

IV. QUANTUM RANDOM NUMBER GENERATION

In recent decades of the digital era, the generation of random numbers has played a significant role across many fields. For example, in science, randomness is required in simulations and physical tests, while in technology it is essential for cryptography and the coordination of computer networks. Even in everyday life, randomness is utilized, e.g., in lotteries and games [12,13]. However, true randomness is considered impossible to achieve in classical processes. Most computer systems that require random bits are based on pseudo-random algorithms. These algorithms are able to generate strings of 0s and 1s, in which strong long-range correlations can be observed [12]. This limitation is negligible in some applications, where the mere appearance of randomness is sufficient; however, in others, such as secure systems, such behavior is unacceptable. This critical requirement for true randomness can, however, be satisfied through quantum mechanics, which are inherently unpredictable by nature [12–14].

A quantum random number generator (QRNG) is a system that exploits fundamental principles of quantum mechanics to produce true randomness. In QRNG, a qubit can be prepared in superposition, which means that it represents two distinct basis states at the same time. This condition can refer to polarizations of photon or spins of electron. Only upon the measurement the outcome collapses to one of these basis states, which is intrinsically random. It means that the measurement outcome can never be predicted [12]. However, the measurement of quantum states in superposition alone does not ensure true randomness. Depending on the level of trust in the system, the ability to characterize its components, and the quantum mechanisms involved, QRNGs can be classified into three categories: trusted-device, self-testing, and semi-self-testing [12–14].

Trusted-device QRNG, also named practical [12], can be used to generate randomness from various quantum processes that are basing on e.g. optics, or radioactive decay. These are the types of entropy sources from which randomness can be obtained. However, there is also a need of detection system, which usually introduces noise to the result of measurement. This aspect can affect output randomness, and for this reason, trusted-device QRNG is not only basing on detection, but also on modelling. It means that either we fully trust the output from a QRNG system that was supplied be a manufacturer or we have well characterized quantum process and included realistic components to extract true randomness. High availability of the optic components, but also their high-quality and rich choice of implementations have made that most existing practical QRNGs are based on quantum optics [12-13]. One of the simplest QRNGs are basing on single photon detection. In such generator, photon can be originally prepared in a superposition of horizontal and vertical polarization. Next, photon is incident on photon beam splitter (PBS) that is transmitting photons with horizontal polarization and reflects photons with vertical one. Under this condition, photon can be either reflected and detected on single photon detector (SPD) or transmitted and detected on another SPD. However, this realization of QRNG has limitation of generation rate coming from realistic components, typically SPDs. Some other realizations of single-photon based QRNGs are allowing to increase generation rate by dividing the random output to higher amount of bits [12].

Practical QRNG can be easily realized; however, some implementations may deviate from theoretical models. This affects the extraction of randomness from noisy measurement outputs. As a result, the generated quantum key can be compromised [12]. To avoid this, the randomness of the output can be verified regardless of the implementation. The method is based on testing the violation of Bell inequalities, which provides a statistical approach to estimating randomness in self-testing QRNG [12,14]. This realization of QRNG relies on two devices that generate quantum outputs. These devices are controlled by input signals, e.g., x and y, one for each device, producing outputs a and b, respectively. The inputs and outputs are then correlated through a function, e.g., Clauser-Horne-Shimony-Holt (CHSH):

$$\mathrm{I} = \sum_{x,y} (-1)^{xy} \left[P(a = b|xy) - P(a \neq b|xy)\right],$$

where P(a=b|xy) and P(a≠b|xy) denote the probabilities that a equals b or does not equal b, given at the settings x and y. If the measured devices are isolated from each other and the principles of quantum mechanics apply, then after a series of measurements the estimation of the function $\mathrm{I} \approx \tilde{\mathrm{I}}$can determine the lower bound of min-entropy. In this case, if $\tilde{\mathrm{I}} \leq 2$, the bound is zero, which means that the outputs are deterministic [13]. However, if this inequality is violated, it indicates the non-local character of the measured devices. This means that the output originates from entangled systems, which implies the involvement of quantum mechanisms. Such certification guarantees the presence of randomness, which can be extracted into a random string of bits [12,13]. Self-testing QRNG ensures the highest level of security and does not rely on the specific implementation of the quantum system. Nevertheless, this approach requires particular conditions, such as entanglement, and the rate of randomness is limited. This is due to the fact that not every correlation between inputs and outputs will violate the CHSH inequality [12,13].

The last implementation of QRNG is based on trust in either the source or the measurement device. In source-independent QRNG, the measurement device is well characterized and can be manipulated. First, it has to be set in such a way that it measures the state of the source's output, e.g. $|+\rangle$. This state corresponds to both $|0\rangle$ and $|1\rangle$ eigenstates. If the source emits the $|+\rangle$ state according to quantum mechanics, the output of the measurement device will produce a string of $|0\rangle$ and $|1\rangle$ in random order. However, to verify this, the measurement device can occasionally be switched to measure either the $|+\rangle$ or $|-\rangle$ state. In this way, certification of the output randomness is realized [12].

The opposite situation occurs when the source is well characterized and controlled, while the measurement device is untrusted. This approach is called measurement-device-independent QRNG, which shows some similarities. Here, the source primarily emits the $|+\rangle$ state. Again, the measurement output should yield either $|0\rangle$ or $|1\rangle$. However, the source can occasionally be changed to emit $|0\rangle$. This process allows to verify whether the measurement device is truly basing on the source output [12]. Various realizations of QRNG have been proposed recently, driven by the demand for randomness in scientific and technological fields. While trusted-device QRNG prioritizes the generation rate of randomness over security aspects, self-testing QRNG ensures secure distribution of quantum keys at the expense of speed. Between these realizations lies semi-self-testing QRNG, which enables both secure generation of random bit strings at a reasonable speed [12].

V. ADVANCES IN QUANTUM COMPUTING FOR REAL-TIME HIGH-ENERGY PHYSICS DATA PROCESSING

The field of quantum computing is currently growing rapidly. A large number of articles on data processing algorithms are being published, reporting on developments in quantum computing. The computing power of quantum computers is growing rapidly, enabling increasingly advanced calculations. The approaching era of Intermediate-Scale Quantum computers will bring the world closer to the construction of computing systems that can reliably process data in real time. This section presents selected achievements in the development of quantum computing, including those carried out under the auspices of CERN, selecting articles that demonstrate potential in real-time data processing. One of the biggest challenges facing the field of quantum computing is adapting operations that are commonly used in classical computing. In typical software or electronic systems, it is common to find blocks that count or perform simple mathematical operations (e.g. addition, multiplication, or division).

For example, let's take a simple adder block. An adder, in the broad sense of the term, without an additional saturation signal, consists of XOR gates to calculate the result of the combination of two bits and AND gates to indicate a carry signal. As a result, we obtain the value a + b mod N, where a and b are input vectors, and N is the maximum number that can be obtained in the summing block. If the vectors a and b have identical bit lengths, we need 2*na bits at the input and at most na+1 bits at the output. When transferring this to quantum computers, it should be noted that quantum gates are reversible by default, which means that the number of qubits at the input is identical to the number of qubits at the output [15]. Therefore, transferring the same operation requires 2 CNOT gates for addition and a CNOT gate along with 2 Toffoli gates for the Carry operation, which consequently requires as many as 3n qubits [16]. For example, for two 16-qubit numbers, we need 32 bits at the input and 18 bits at the output, while for operations on quantum computers, we need as many as 48 qubits. An alternative approach is to perform the same operation using the quantum Fourier transform. As a result, this allows the number of qubits required to be reduced to 2n. [17].

An interesting example of the application of data processing methods is the use of algorithms from the Machine Learning group. The selected group of algorithms is increasingly used, also in real-time processing, e.g., in CMS Level-1 Trigger, where most subsystems for the high-luminosity phase of the LHC will implement one of the algorithms from this group. Quantum computers already show potential for use in data processing using neural networks – the classification quality of quantum neural networks is similar to the classical neural networks [18,19]. Unfortunately, there is a lack of more data that could indicate shorter processing times or lower resource usage for quantum algorithms. Quantum computing is still in the early stages of development. There is insufficient research into the processing of large amounts of data, real-time data processing, and optimization of basic arithmetic algorithms. However, several issues should be noted:

- Quantum computers will not necessarily replace classical computers in all operations, particularly in the field of simple mathematical operations or bit data processing.
- In some cases, the classical approach, e.g., using ASICs, GPUs, or FPGAs, currently offers shorter data processing times [20].
- Low stability of quantum computers over longer periods of time [21] makes it impractical to perform operations similar to ones implemented in FPGA.
- The parameters such as resource availability, data processing speed, and reliability will improve in the future.
- When transitioning from classical to quantum algorithms, a change in mindset is needed. It should be noted that the available quantum gates allow for easier execution of operations that require more complex operations in classical computers (e.g., the Fourier transform) [22], and that quantum gates themselves are reversible by definition.

Will this allow quantum computers to be widely used for real-time data processing? It is difficult to answer the question today, although their potential is already apparent. In certain aspects of data processing, there is still a long way to go before quantum supremacy can be achieved. Currently, QC can be used in simulations of particle interactions or entire experiments, if their properties allow for quantum representation [23]. However, real-time data processing would require stable and reliable quantum computing accelerators, as well as more advanced research in quantum algorithm.

VI. QUANTUM ATTENTION MECHANISMS IN NEURAL NETWORKS

Attention mechanisms, originally formalized in the Transformer architecture, assign context-dependent weights to features based on the similarity between queries and keys, producing weighted combinations of values for downstream tasks. The standard scaled dot-product attention computes:

$$\mathrm{Attention}(Q, K, V) = \mathrm{softmax}((QK^{\top})/\sqrt{d})V,$$

where Q, K, and V are the query, key, and value matrices and d is the embedding dimension [24]. Despite their success, the quadratic complexity and limited expressivity of classical similarities have motivated the exploration of quantum-based enhancements [25]. The term quantum-inspired refers to algorithms that leverage mathematical structures from quantum mechanics (e.g., superposition, entanglement, Hilbert spaces) without necessarily requiring quantum hardware, aiming to enrich the representational capacity and efficiency of classical models.

In quantum-inspired attention, classical features may be encoded into high-dimensional Hilbert spaces via amplitude or phase encoding, drawing analogies to quantum state vectors, which enrich similarity measures beyond real-valued dot products. Superposition allows feature vectors to represent multiple states simultaneously, while constructs analogous to entanglement capture nonlocal dependencies, enabling richer interaction modeling among tokens [26]. Instead of computing standard linear similarity, quantum-inspired approaches may use quantum kernel functions to measure similarity, theoretically expanding the feature space exploited by attention modules. Recent work falls into several categories: mixed-state and self-attention mechanisms, exemplified by the Quantum Mixed-State Self-Attention Network (QMSAN), which merges classical attention with quantum mixed states to estimate similarity in the quantum domain, improving robustness and sequence modeling in NLP tasks; quantum hard attention, inspired by Grover's search algorithm, as in GQHAN, which addresses non-differentiability in discrete attention choices and demonstrates enhanced performance and noise robustness; and hybrid classical-quantum transformers, which integrate quantum-enhanced attention layers into classical pipelines, offering potential advantages in feature richness and representational coherence while maintaining compatibility with existing deep learning frameworks [27]. These hybrid methods typically embed classical features into quantum-state representations, apply parameterized quantum updates, and use measurement outcomes to compute attention scores [27]. A related line of work uses quantum concepts to induce sparsity in attention matrices, alleviating the $O(n^2)$ cost of classical attention for long sequences. For example, Quantum-Inspired Sparse Attention Transformers (QSAT) leverage superposition and entanglement to focus computation on semantically significant token interactions, reducing redundant calculations. Quantum-inspired attention has also been applied beyond sequence modeling, including aspect-based sentiment analysis, where quantum cross-attention mechanisms improve the fusion of syntactic and semantic features, and vision and structured data tasks, where it enhances spatial and relational feature interactions in vision transformers and graph neural networks [26].

While conceptually compelling, challenges remain, including hardware limitations due to current quantum processor constraints, scalability and practical benefits relative to optimized classical attention, and theoretical foundations, such as rigorous demonstrations of expressivity and generalization [25][26]. Despite these challenges, quantum-inspired methods provide a rich source of interdisciplinary research at the nexus of physics, computation, and machine learning. Overall, quantum-inspired attention mechanisms represent on a promising direction, blending quantum information principles with deep learning architectures, where hybrid approaches, quantum kernel similarity, and sparse attention methods offer avenues for enhanced representational capacity and computational efficiency, and future work will likely focus on bridging theoretical advances with practical, scalable implementations [24][27].

VII. DISCUSSION AND CONCLUSIONS

Utilizing quantum technologies is a task that requires precise control methods and interdisciplinary approach. Quantum state encoded in single photons or trapped atoms and ions is fragile due to its interaction with environment. Preparing quantum states, performing operations and state measurement have to be implemented in replicable way and become more complicated with increasing basis dimensions or number of quantum states in a system. Deterministic and scalable single photon sources are necessary in obtaining high-dimensional quantum states, but many approaches are possible. Enlarging quantum information transmitted per photon could be useful in practical realization of quantum algorithms. Precise cooling methods below Doppler limit are required in working on neutral atoms or ions and performing quantum operations on them. Applications of quantum technologies are still being developed and their promising character is visible on the theoretical level. Some of them have already been implemented at the hardware level, often in the form of commercially available devices, like quantum random number generators, quantum key distribution systems or quantum computing processors. Enlarging set of applications and working on quantum technologies above fundamental research is a prospective task.

REFERENCES

[1] McLaren, M., Mhlanga, T., Padgett, M. et al. Self-healing of quantum entanglement after an obstruction. Nat Commun 5, 3248 (2014). https://doi.org/10.1038/ncomms4248

[2] Ohad Lib and Yaron Bromberg, "Spatially entangled Airy photons," Opt. Lett. 45, 1399-1402 (2020)

[3] Xiao Liu, Daniel I. Shahar, Dong Beom Kim, Virginia O. Lorenz, and Siddharth Ramachandran, Generation and engineering of orbital angular momentum biphotons in optical fibers, Optica Quantum 3, 280-288 (2025)

[4] B. Chen, et al. Bright solid-state sources for single photons with orbital momentum, 16(3):302-307, 2021 Nat Nanotechnol., https://doi.org/10.1038/s41565-020-00827-7

[5] Cuo Wu et al. Room-temperature on-chip orbital angular momentum single-photon sources. Sci. Adv.8,eabk3075 (2022). https://doi.org/10.1126/sciadv.abk3075

[6] Sultanov, V., Kavčič, A., Kokkinakis, E. et al. Tunable entangled photon-pair generation in a liquid crystal. Nature 631, 294–299 (2024). https://doi.org/10.1038/s41586-024-07543-5

[7] Mukherjee, P. K. (2024). Effects of quantum dots on the properties of ferroelectric liquid crystal. Liquid Crystals, 51(1), 27–32. https://doi.org/10.1080/02678292.2023.2272154

[8] Polarized and Bright Telecom C-Band Single-Photon Source from InP-Based Quantum Dots Coupled to Elliptical Bragg Gratings, Zhenxuan Ge, Tunghsun Chung, Yu-Ming He, Mohamed Benyoucef, and Yongheng Huo, Nano Letters 2024 24 (5), 1746-1752 https://doi.org/10.1021/acs.nanolett.3c04618

[9] LaPierre, Ray. (2022). Atom Cooling and Trapping. https://doi.org/10.1007/978-3-031-12432-7_21

[10] Bernardini, Francesco & Chakraborty, Abhijit & Ordonez, Carlos. (2023). Quantum computing with trapped ions: a beginner's guide. European Journal of Physics. 45. https://doi.org/10.1088/1361-6404/ad06be

[11] Kowalski, Krzysztof & Van, Cao & Khoa, Dinh & Głódź, Małgorzata & Nguyen, Bang & Szonert, Jerzy. (2010). Magneto-optical Trap: Fundamentals and Realization. Computational Methods in Science and Technology. Special Issue. 115-129. https://doi.org/10.12921/cmst.2010.SI.02.115-129

12] X. Ma, et al. Quantum random number generation, 2, 16021, 2016 npj Quantum Information, https://doi.org/10.1038/npjqi.2016.21

[13] M. Herrero-Collantes and J. C. Garcia-Escartin, Quantum random number generators, Vol. 89, No. 1, 2017 Rev. Mod. Phys., https://doi.org/10.1103/RevModPhys.89.015004

[14] J. E. Jacak et al., Quantum random number generators with entanglment for public randomness testing, 10, 164, 2020, Sci Rep, https://doi.org/10.1038/s41598-019-56706-2

[15] Barenco, Adriano, et al. “Elementary Gates for Quantum Computation.” Physical Review A, vol. 52, no. 5, Nov. 1995, pp. 3457–67. Crossref, https://doi.org/10.1103/physreva.52.3457

[16] Draper, Thomas, “Addition on a Quantum Computer”, Aug 2000, https://doi.org/10.48550/arXiv.quant-ph/0008033

[17] Atchade-Adelomou, Parfait, Gonzales Saul “Addition on a Quantum Computer, Efficient Quantum Modular Arithmetics for the ISQ Era”, Nov 2023, https://doi.org/10.48550/arXiv.2311.08555

[18] Casals, Mikel and Belis, Vasilis and Combarro, Elias F and Alarcón, Eduard and Vallecorsa, Sofia and Grossi, Michele, “Guided Graph Compression for Quantum Graph Neural Networks”, Machine Learning: Science and Technology, vol. 6, no. 3, Sep. 2025, p. 35-48, http://dx.doi.org/10.1088/2632-2153/adffe2

[19] Deepak Gupta and Himanshu Pandey and Ratikanta Behera, “Wavelet-Accelerated Physics-Informed Quantum Neural Network for Multiscale Partial Differential Equations”, 2025, https://doi.org/10.48550/arXiv.2512.08256

[20] Battistel, F., et al. “Real-Time Decoding for Fault-Tolerant Quantum Computing: Progress, Challenges and Outlook.” Nano Futures, vol. 7, no. 3, Aug. 2023, p. 032003. Crossref, https://doi.org/10.1088/2399-1984/aceba6

[21] Samudra Dasgupta, “Stability of Quantum Computers”, 2024, https://doi.org/10.48550/arXiv.2404.19082

[22] Giuseppe Luca Celardo and Carlos Pineda and Marko Žnidarič, “Stability of quantum Fourier transformation on Ising quantum computer”, 2003, https://doi.org/10.48550/arXiv.quant-ph/0310163

[23] Cindy Tran and Tanaporn Na Narong and Eric S. Cooper, “Modeling Quantum Enhanced Sensing on a Quantum Computer”, 2022, https://doi.org/10.48550/arXiv.2209.08187

[24] A. Vaswani et al., “Attention Is All You Need,”NeurIPS, 2017.

[25] C. Child et al., “Generating Long Sequences with Sparse Transformers,” 2019.

[26] M. Schuld, I. Sinayskiy, F. Petruccione, “Quantum Machine Learning: An Overview,” Contemporary Physics, 2019.

[27] F. Chen et al., “Quantum Mixed-State Self-Attention Network,” 2024.