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Influence of IQT on research in ICT, part 4

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***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*—ICT, QIT, biomedical engineering, electronics and communications engineering, sensors, quantum machine learning, quantum Internet, quantum computing, cybersecurity, quantum networks, quantum sensors**

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.

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II. Simulation of Quantum Dot Dynamics in a Radiation Field Using QuTiP

A. Introduction

Quantum dots (QDs) are small semiconducting crystals with quantum mechanical properties [1]. They are nanometer-sized semiconductor particles that exhibit unique optical and electronic properties due to quantum confinement, where the movement of electrons is restricted to discrete energy levels. These energy levels enable quantum dots to emit photons at specific wavelengths when excited, making them valuable for a range of applications including photonics, bio-imaging, and sensing technologies. Among various types of quantum dots, rare-earth doped QDs such as those incorporating europium (Eu) and terbium (Tb) stand out for their sharp emission peaks and long-lived excited states. Europium-doped QDs, in particular, are notable for their characteristic red photoluminescence, which arises from energy transitions within the europium ion (Eu^{3+}) itself. The unique luminescence properties of europium ions make Eu-doped QDs especially useful in optical sensing and biomedical applications. Their photo-stability and specific emission wavelengths are advantageous for bio-imaging, allowing for long-duration imaging without photo-bleaching. Currently, a significant amount of research is aimed at using the unique optical properties of QDs in biological imaging [2]. Furthermore, the discrete energy transitions of Eu^{3+} ions provide highly defined spectroscopic signals that are sensitive to environmental changes, such as exposure to radiation. This sensitivity opens potential for designing Eu quantum dot-based radiation sensors, where interactions with external electromagnetic fields can induce transitions that are observable via changes in photoluminescence. Understanding and simulating these interactions are essential steps for developing QD based devices optimized for radiation detection and other sensing applications. In this study, we simulate the behavior of a europium quantum dot in the presence of an external radiation field using Quantum Toolbox in Python (QuTiP).

B. Theory and Model of Quantum Dot-Radiation Interaction

QDs are semiconductor nanocrystals whose unique optical and electronic properties are governed by quantum confinement, resulting in discrete energy levels that differ from bulk materials. In rare-earth doped quantum dots, such as those incorporating europium ions (Eu3+), these energy levels facilitate sharp, characteristic emissions due to electronic transitions [1], [2]. For simplicity, europium-doped QDs can be modeled as a two-level system comprising a ground state $\langle 0|$ and an excited state $|1\rangle$. This two-level approximation is suitable for representing the primary optical transitions between the lowest electronic energy states of the Eu^{3+} ion, where the system absorbs energy from the radiation field, allowing for transition from $\langle 0|$ to $|1\rangle$. The rate and nature of these transitions provide insight into the interactions between the quantum dot and the radiation field [3] also the study of the defects induced by radiation led to better devices [4]

1) Hamiltonian of the Quantum Dot-Radiation System: To develop a correct theoretical description of the system, it is essential to take into account multi-particle interactions [3], [5]. To capture the dynamics of the Eu quantum dot in a radiation field, we define a Hamiltonian H for the system. The total Hamiltonian consists of three main components:

Quantum Dot Hamiltonian H_{dot}: Represents the energy levels of the Eu quantum dot itself.

Radiation Field Hamiltonian $H_{radiation}$: Models the external radiation field applied to the quantum dot.

Interaction Hamiltonian $H_{interaction}$: Describes the coupling between the radiation field and the QD's energy levels.

Thus, the full Hamiltonian H expressed as:

$$H = H_{\text{dot}} + H_{\text{radiation}} + H_{\text{interaction}} \tag{1}$$

Quantum Dot Hamiltonian H_{dot}: The quantum dot energy levels are defined by the energy gap E_{Eu} between the ground and excited states:

$$H_{dot} = E_{Eu}\langle 0||1\rangle \tag{2}$$

Where E_{Eu} is the energy associated with the transition.

Radiation Field Hamiltonian $H_{radiation}$: The radiation field is modeled as a monochromatic oscillating field, with frequency $\omega_{radiation}$. This is commonly represented by a Pauli σ_x term to indicate the oscillatory effect of the field:

$$H_{radiation} = \omega_{radiation}\sigma_x \tag{3}$$

Interaction Hamiltonian $H_{interaction}$: The interaction between the quantum dot and the radiation field is described by a coupling term with strength g , which defines how strongly the field interacts with the dot's energy states. This is also typically represented using the Pauli σ_x operator:

$H_{interaction}$ = g σ_x eqn(4)

2) Time-Dependent Schrodinger Equation and Evolution: The time evolution of the quantum dot's state under this Hamiltonian is governed by the time-dependent Schrodinger equation:

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t) = \hat{H}\Psi(\mathbf{r},t), \tag{4}$$

where i is the imaginary unit, $\hbar$ is the reduced Planck's constant, $\Psi(\mathbf{r},t)$ is the time dependent wave function, and $\hat{H}$ is the Hamiltonian operator.

Solving this equation allows us to observe how the radiation influences the QD's transitions over time. We simulate the time evolution of the europium QD's state in response to the radiation field using QuTiP, which numerically solves the Schrodinger equation [4]. By examining the expectation values of Pauli operators over time, we gain insight into the dot's behavior and how the quantum state oscillates between ground and excited states in response to the radiation [6].

Through this approach, we can visualize how variations in parameters like $E_{Eu,}$ $\omega_{radiation}$, and g influence the quantum dot's dynamics. This model provides a foundational understanding of the interaction between europium quantum dots and external radiation, which is critical for designing efficient radiation-responsive sensors based on rare-earth-doped quantum dots [4], [6].

3) Simulation of Quantum Dot Dynamics Using QuTiP: In the simulation, we set up the parameters E_{Eu}, $\omega_{radiation}$ and g , which define the Eu quantum dot's energy levels, the radiation field's frequency, and the coupling strength between the dot and the field, respectively. We initialize the quantum dot in the ground state —0¿ and use the full Hamiltonian H = H_{dot} + $H_{radiation}$ + $H_{interaction}$ to simulate how the state changes over time due to the interaction with the radiation field. For analysis, we calculate the expectation values of the Pauli matrices sigma_x, sigma_y , and sigma_z over time, which reveal insights into the quantum dot's oscillatory behavior between ground and excited states. These expectation values indicate the likelihood of finding the quantum dot in each state at a given time and reflect the influence of the radiation [7].

4) Analytical Interpretation of Dynamics: By examining the time evolution of the expectation values, we can draw several conclusions about the quantum dot's response to the radiation field. When the quantum dot is exposed to radiation near its resonant frequency (matching E_{Eu}), the oscillations in the expectation values are more pronounced, indicating strong transitions between the ground and excited states [8], [9]. The frequency of these oscillations reflects the coupling strength g and the detuning between E_{Eu} and $\omega_{radiation}$ This resonance condition is essential for maximizing the QD's response, which is critical for sensor applications. If the radiation field is applied continuously, the system may reach a steady-state oscillation, where the probabilities of being in the ground or excited states remain stable. This behavior suggests the quantum dot has achieved a dynamic equilibrium with the radiation field, which can be leveraged in continuous monitoring applications. Varying parameters like g (the interaction strength) and $\omega_{radiation}$ (radiation frequency) allow us to explore how sensitive the quantum dot is to external conditions [9]. For instance, a stronger coupling constant g enhances the transition probability, making the quantum dot more responsive to radiation. Similarly, tuning $\omega_{radiation}$ near resonance with E_{Eu} maximizes the induced transitions, which can optimize the dot's sensing capabilities.

```
import numpy as np
import matplotlib.pyplot as plt
from qutip import *

# Parameters for the Europium quantum dot
E_Eu = 1.5 # Energy gap for Eu ion transition (arbitrary units)
omega_radiation = 2  # Radiation field frequency to match E_Eu
g = 0.05  # Coupling strength between the radiation and Eu levels

# Define the two-level system (quantum dot)
ground_state = basis(2, 0)  # Ground state |0>
excited_state = basis(2, 1)  # Excited state |1>

# Define Hamiltonian components
H_Eu = E_Eu * excited_state * excited_state.dag()  # Eu ion energy levels
H_radiation = omega_radiation * sigmax()            # Radiation field
H_interaction = g * (sigmax())                      # Interaction Hamiltonian

# Total Hamiltonian
H_total = H_Eu + H_radiation + H_interaction

# Initial state (Eu in ground state)
psi0 = ground_state
```

Fig. 1. Simulation code snippet

C. Simulation Methodology

This section details the setup and execution of the simulation, which uses the QuTiP sesolve package to model and solve the time-dependent behavior of europium-doped quantum dots in a radiation field. QuTiP provides tools for quantum simulations, making it suitable for calculating the dynamic interactions between the quantum dot and the radiation field as governed by the system Hamiltonian. The simulation allows us to observe how the QD's state evolves over time and to analyze the effects of radiation on the transition dynamics [6].

1) Simulation Parameters and Setup: In this model, we use the parameters: Energy Gap E_{Eu}: This represents the separation between the ground state $\langle 0|$ and excited state $|1\rangle$ of the Eu quantum dot. It is a critical parameter, as the radiation frequency must match or approach this gap for resonance.

Radiation Field Frequency $\omega_{radiation}$: The frequency of the applied radiation, which can be adjusted to achieve resonance or off-resonance interactions with the quantum dot.

Coupling Strength g : Represents the strength of interaction between the quantum dot and the radiation field, influencing how strongly the field affects the transitions between states.

We initialize the Eu quantum dot in the ground state $\langle 0|$ and define the Hamiltonian components H_{dot}, $H_{radiation}$, and $H_{interaction}$ as outlined in the theory section. The total Hamiltonian H as defined in eqn(1), is then used to model the system's dynamics.

2) Simulation Execution: Using QuTiP, we simulate the time evolution of the Eu quantum dot by solving the time-dependent Schrodinger equation [8], [9]. We used QuTiP's sesolve function to compute the quantum state's evolution over time, given the Hamiltonian. The simulation produces the expectation values of the Pauli matrices σ_x, σ_y, and σ_z, which is plotted in 2D and help to visualize the QD's behavior under the radiation field. The code snippet is shown bellow.

D. Results and Analysis

We obtained simulation for interaction with X-ray and Gamma ray. With 2, 4, 6 and 8 eV of energy as shown below

```
# Time evolution settings
time_range = np.linspace(0, 10, 100)  # Time range for simulation (0 to 10 units)

# Solve the time-dependent Schrodinger equation
result = sesolve(H_total, psi0, time_range, [sigmax(), sigmay(), sigmaz()])

# Plot the expectation values over time
plt.figure(figsize=(6, 4))
plt.plot(time_range, result.expect[0], label="Expectation X")
plt.plot(time_range, result.expect[1], label="Expectation Y")
plt.plot(time_range, result.expect[2], label="Expectation Z")
plt.xlabel("Time (microseconds)")
plt.ylabel("Expectation Values")
plt.legend(loc='upper right')
plt.title("Quantum Dot Under 2.0eV Radiation Energy")
plt.show()
```

Fig. 2. Simulation code snippet

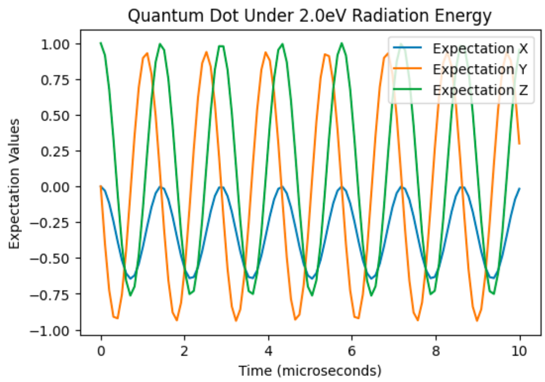

Fig. 3. Plot of expectation value of quantum dot under 2.0eV radiation energy

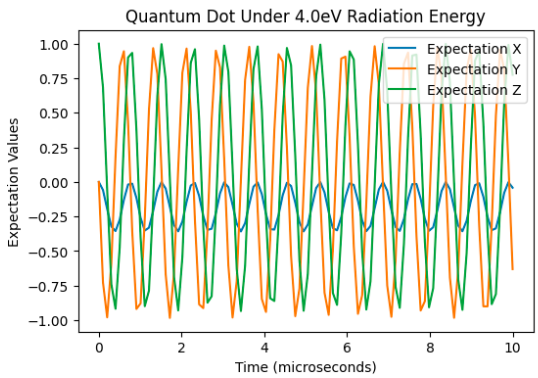

Fig. 4. Plot of expectation value of quantum dot under 4.0eV radiation energy

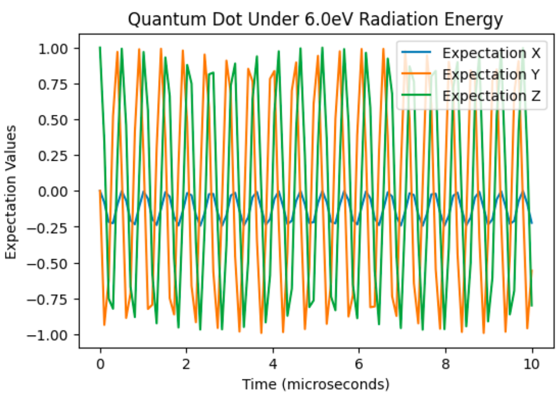

Fig. 5. Plot of expectation value of quantum dot under 6.0eV radiation energy

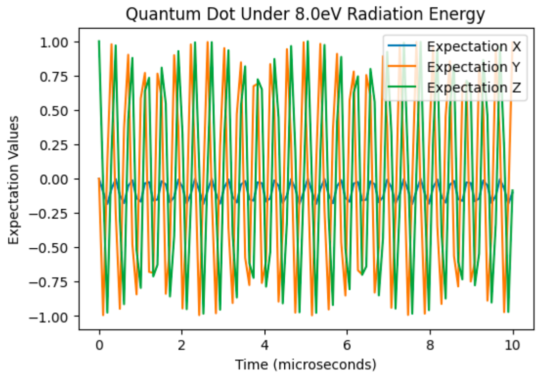

Fig. 6. Plot of expectation value of quantum dot under 8.0eV radiation energy

Figure 3 shows the response obtained of the dynamics of the QDs with varying radiation frequency from near radiation frequency of 2.0 to around 8.0 in steps of 2.0. In this section, we analyze the outcomes of our simulation, focusing on how the parameters of the quantum dot and radiation field affect the state transitions, the system's response to different radiation frequencies, and the overall behavior of the europium-doped quantum dot in a radiation environment. The simulation also reveals how the system approaches a steady state under continuous radiation of $\omega_{\text{radiation}} = 2.0$. This steady-state behavior is characterized by consistent oscillations in the expectation values, implying that the quantum dot has reached a dynamic equilibrium. In practical applications, this steady state could be used to monitor stable radiation levels over time, providing real-time feedback on radiation exposure. However, at a radiation frequency significantly higher than the QD's resonance frequency (e.g., 8.0 as compared to the QD's natural frequency near 1.5), the radiation field is "detuned" from the quantum dot's intrinsic energy gap. This effect arises from the interference between the two oscillations and manifest as amplitude modulation in the observed response.

E. Conclusion

This report demonstrates the theoretical and simulated behavior of europium-doped quantum dots under radiation exposure, exploring their potential as radiation-sensitive materials in quantum sensing applications. By analyzing the system dynamics through time-dependent simulations, we observed the impact of parameters such as radiation frequency, and coupling strength on the QD's response. These findings indicate that europium-doped quantum dots hold significant promise for applications in medical diagnostics, environmental monitoring, and advanced photonic devices. This work lays the groundwork for future experimental research and development. With advances in computational power more sophisticated models could refine these insights, bringing us closer to the practical deployment of quantum dots in radiation-sensitive applications.

III. Quantum Methods in Energy Storage

Currently we can observe the dynamic growth of renewable energy sources, such as solar and wind power. It causes significant challenges in maintaining of electric power system as those inconstant energy sources connected to power grids disrupt the stability. Traditional energy storage methods have important limitations, which force us to look for improvements in this area. Quantum methods of energy storage can address those methods and as a result provide us more effective way to maintain the power grids.

A. Quantum supercapacitors

The capacitance of traditional supercapacitors (Electrical Double-Layer Capacitors - EDLC) relay on EDLC capacitance and pseudocapacitance. Both capacitances are only separable by measurement techniques. The amount of charge stored per unit voltage in an electrochemical capacitor is primarily a function of the electrode size, although the amount of capacitance of each storage principle can vary extremely. The integration of quantum mechanics into these systems has led to the concept of quantum capacitance, a parameter intrinsically linked to the electronic density of states and the local potential of electrode materials. The researchers [10] suggest that increasing the quantum capacitance in EDLC supercapacitors can cause significant capacitance increase. It can be achieved by engineering of electrode surfaces by dopants, functional groups, or structural defects.

In theory, quantum capacitance can be represented by mathematical expressions linking in to the local potential (φG) and the density of the electrode material. Quantum capacitance (QC) can be determined using the equation [11]:

$$QC = e^2 \int_{-\infty}^{+\infty} DOS(E)\ F_T\,(E - \varphi_G)\,dE \tag{5}$$

$$F_T(E) = \frac{1}{4K_BT} Sech^2\left(\frac{E}{2K_BT}\right) \tag{6}$$

Development of two-dimensional materials, such as graphene and transition metal chalcogenides exhibit exceptional conductivity and surface area, which are critical for optimizing quantum capacitance. It was proved by authors [10] that relationship between number of graphene layers and quantum capacitance can be clearly observed.

B. Quantum Batteries

The quantum batteries, unlike the quantum supercapacitors, are currently theoretical devices. They represent paradigm shift in energy storage, utilizing discrete quantum states, such as superposition and entanglement, to store energy. Classical batteries operate on the basis of thermodynamic charge transfer between anode and cathode in electrolytic environment. Quantum batteries exploit quantum mechanical principles to enable phenomena such as 'quantum charging acceleration', which allows for a quadratic scaling of charging speed with the number of entangled cells, significantly outperforming the linear scaling observed in classical counterparts [12].

Additional important aspect of quantum batteries is utilizing quantum mechanics to improve their energy density. Two main proposals include storing energy in nuclei excitations and nanovacuum tubes. Quantum batteries are a part of the broader field of quantum energy, which shows the role that quantum mechanics plays in the storage, conversion and transport of energy [13].

C. Summary

Two main methods of quantum energy storage described above are actively explored path in science. They are considered as potentially effective, cheap and durable energy storage methods which are necessary to maintain energy generated by renewable energy sources. However it have to be kept in mind that moving from theoretical models into real, scalable and durable market product requires huge effort both on scientific and manufacturing side.

IV. Dynamic Storyline and Content Optimization in Interactive Educational Games Using Quantum Computing, AI, and AR: A Conceptual Study

A. Introduction

Interactive educational games are increasingly becoming a cornerstone of modern learning, particularly in teaching English as a second language [14]. By leveraging advanced technologies such as Quantum Computing (QC), Artificial Intelligence (AI), and Augmented Reality (AR), these games can create dynamic storylines and optimize content to enhance user experience. This conceptual study explores the potential integration of these technologies to revolutionize educational systems [15]–[17].

B. Dynamic Storyline Optimization Using Quantum Annealing

Dynamic storylines are narrative structures that adapt to user input, enabling personalized and engaging learning experiences. The complexity of designing such narratives grows exponentially with user variability and branching scenarios. Quantum Annealing (QA) offers an efficient solution to address these challenges [18].

QA allows quantum systems to identify the best storyline paths among numerous possibilities by utilizing principles of superposition and quantum tunneling. This algorithm can adiabatically navigate vast solution spaces to identify the optimal ground state based on user actions and preferences [19]. In the context of language learning games, QA can adjust the difficulty level of the storyline in real time, fostering adaptive and dynamic learning experiences.

The advantages of QA in solving large-scale optimization problems make it an ideal technology for educational games. By leveraging this algorithm, games can manage adaptive content with unprecedented speed and accuracy, unattainable through conventional methods [20].

C. AI-Driven Content Customization

Artificial Intelligence plays a critical role in personalizing educational content for individual learners. By employing Natural Language Processing (NLP), AI can analyze user behavior, linguistic patterns, and preferences to generate adaptive content [21], [22].

In interactive games, AI-driven systems can generate real-time dialogue options based on the player's language proficiency [23]. Additionally, AI can analyze speech input to detect pronunciation and grammar errors, providing instant corrective feedback [24]. AI also predicts user competency levels and recommends suitable challenges or tasks [25]. With deep learning models, AI can continually improve the system's accuracy and adaptability [26].

However, AI algorithms require extensive training data and computational resources, which can be augmented by Quantum Computing to enhance their performance [27]. This integration enables systems to efficiently deliver personalized and responsive learning experiences.

D. Augmented Reality for Immersive Language Learning

Augmented Reality bridges the gap between digital and physical environments, offering immersive experiences for learners. By integrating AR into educational games, players can interact with virtual objects and scenarios that facilitate practical language application [28], [29].

In English language learning, AR can be used for various activities, such as identifying and labeling objects in the real world using AR overlays [30], or simulating real-life scenarios like ordering food in a restaurant or asking for directions [31]. Gamified tasks can also be integrated with AR, such as AR English Quest where players follow clues and interact with AR-based prompts to practice language skills [32].

The integration of AR with QA and AI allows for real-time content rendering and contextual adaptation, enhancing the fluidity and engagement of the learning experience.

E. Synergy of Quantum Annealing, AI, and AR

The combined application of Quantum Annealing, AI, and AR offers exceptional opportunities to redefine interactive educational games. Quantum Annealing accelerates AI's ability to dynamically generate and customize content [33], [34]. AR enhances the tangibility of AI-generated content, making learning more engaging [35], [36]. This integration ensures that storylines and content evolve seamlessly in response to user input.

For instance, a game could use QA to analyze player data, AI to design tailored language challenges, and AR to present these challenges in an interactive format. Such synergy ensures a holistic and adaptive learning experience.

F. Conclusion and Future Directions

The integration of Quantum Annealing, AI, and AR into interactive educational games holds immense potential to transform how English and other subjects are taught. While challenges remain, such as technological maturity and resource demands, continued research and development promise to address these barriers.

Future research could focus on developing more efficient QA algorithms for optimizing storylines and content, enhancing AI's adaptability to diverse user profiles and learning objectives, and expanding AR's capabilities to create richer, more immersive educational environments. By leveraging these advanced technologies, the next generation of educational tools can deliver personalized, engaging, and effective learning experiences that meet the diverse needs of learners.

V. Integration of Quantum Technologies in Aviation Applications

A. Introduction

The aviation sector is increasingly challenged by the need for robust and secure communication systems due to its reliance on advanced digital technologies. Conventional communication methods, such as Controller-Pilot Data Link Communications (CPDLC), utilize unencrypted channels, rendering them vulnerable to cyberattacks. To mitigate these risks, innovative hybrid quantum-secure communication protocols have been developed, integrating post-quantum cryptographic techniques. Among these, the PQAG-KEM and PQAG-SIG protocols, introduced by Dowling and Wimalasiri, exemplify the fusion of quantum and classical cryptography to enhance the confidentiality and authenticity of aviation communication systems. These protocols offer superior security features while being resource-efficient, meeting the stringent requirements of avionics environments [37].

By combining classical cryptographic mechanisms with quantum technologies, these hybrid systems address existing limitations in quantum infrastructure. For example, the PQAG-KEM protocol employs pre-distributed public keys to minimize communication overhead and ensures forward secrecy through quantum key encapsulation mechanisms (KEMs). These advances align with Federal Aviation Administration (FAA) guidelines, representing a pivotal step toward implementing quantum-resilient aviation communication systems [37].

B. Optimization of Flight Operations Using Quantum Computing

Quantum computing has emerged as a transformative tool in optimizing flight operations, including trajectory planning and disruption recovery. Makhanov et al. explored the potential of quantum algorithms for flight trajectory optimization, a complex task constrained by fuel efficiency, time minimization, and environmental considerations. Their integration of Grover's algorithm with Dijkstra's shortest path method achieved a quadratic improvement in computational efficiency relative to classical approaches. While current quantum hardware capabilities remain limited, hybrid quantum-classical frameworks show significant promise for real-time air traffic management applications [38].

Additionally, Mori addressed the Aircraft Recovery Problem (ARP), a critical aspect of airline disruption management, by formulating it as a Quadratic Unconstrained Binary Optimization (QUBO) problem. Using hybrid solvers, rapid and cost-efficient solutions to ARP were demonstrated, reducing operational costs and recovery times. This research underscores the feasibility of quantum computing in resolving complex operational challenges, thereby enhancing efficiency and resilience in airline operations [39].

C. Aerodynamic Analysis through Quantum Machine Learning

Quantum machine learning techniques are making notable contributions to aerodynamics. Yuan et al. demonstrated the application of quantum support vector machines (qSVMs) for detecting flow separation on aircraft airfoils, a critical determinant of aerodynamic performance. Their results indicated an 11.1% improvement in binary classification accuracy over classical SVMs, achieving 90.9% accuracy. In multi-class classification, qSVMs exhibited a 17.9% improvement, highlighting their potential to enhance aerodynamic modeling and control. These advancements underscore the role of quantum algorithms in revolutionizing fluid dynamics, with significant implications for aircraft design and performance optimization [40].

D. Conclusion and Future Directions

The adoption of quantum technologies in aviation holds considerable potential for enhancing communication security, operational efficiency, and aerodynamic analysis. Despite the current scalability and noise-related challenges of quantum systems, hybrid approaches provide a viable pathway for immediate implementation. As quantum hardware continues to evolve, these technologies are expected to play an integral role in advancing sustainable and secure aviation operations.

VI. Quantum Integrated Circuits

A. Introduction

The invention of integrated circuit in the late 1950s was a breakthrough which allowed to push for miniaturization and scalability simply impossible with discrete devices. Nowadays, the state of the art manufacturing processes allow to reliably fabricate devices composed of tens of billions of transistors. Over past decades an exponential improvement in performance and/or complexity has been observe and described by empirical relationship called Moor's Law [41].

Quantum integrated circuit is an assembly of quantum components and optional accompanying electronic components, fabricated as a single unit, in which miniaturized devices (e.g. qubits and transistors) and their interconnections are built up on a thin substrate of semiconductor material. Quantum Integrated Circuits leverage quantum mechanical principles to perform computations, processing, sensing and other tasks. Harvesting of the quantum power usually requires creating a special, confined micro-environment thus the precision of modern IC fabrication processing is of great use. One of the first applications of quantum IC was a super accurate reference standard (e.g. 1V NIST standard [42]). Today's ones of the most sophisticated chips ever manufactured by humankind allow us to investigate the advantages and challenges of quantum computing.

B. Quantum Computing Integrated Circuits

Quantum Computer Integrated Circuit refers to monolithic or hybrid chip which realizes array (or matrix) of qubits, supporting chip (e.g. control signal generation) or both.

Similar to the classical computers QC benefits most from the large scale integration as higher the number of qubits, more performant and reliable the computation, especially in the era of noisy intermediate-scale quantum computing we are currently in [43].

1) Ion-trap based quantum computing: Qubits realized on trapped ions are among the most promising platforms for practical quantum computing. The main advantage of this technology is exceptionally long coherence time and high coherence time to gate time ratio. It's possible, and already demonstrated, to achieve as high as 50 s without addition of dynamical decoupling techniques and up to 600 s with the aid of dynamical decoupling [44].

An efficient implementation of multi-qubits computing with these techniques requires an array or matrix of precisely designed, lithographed, and controlled tiny electrodes. These electrodes are used to produce electromagnetic forces that hold ions in place, isolating them from the environment to minimize external coupling and hence limit noise and decoherence. In recent years a lot of effort has been undertaken to not just increase the number of qubits the single chip encapsulates, but also to integrate as much of the control logic into it as possible. For example, researchers demonstrated a hybrid approach in which the precise voltage controller [45] or optics [46] has been integrated into the top electrode. Direct fiber coupling unlocks efficient delivery of light to a trap chip in a cryogenic environment eliminating the need for beam alignment into vacuum systems. As a result increase in parallelization and fidelity has been observed [46], not mentioning the reduction in the number of bulky control apparatuses.

2) Superconducting based quantum computing: One or more Josephson Junctions embedded in a superconducting passive circuit can act as a nonlinear microwave resonator and hence provide another promising platform for practical quantum computing. Quantum mechanical behavior in such qubits is displayed at temperatures in the range of 10 mK. Once electromagnetic coupling between microwave resonator qubits is introduced, a quantum processor is created [47].

The array of superconductive qubits can be engineered monolithically at circuit level allowing for even better (compared to ion traps) utilization of technologies already harvested for fabrication of classical ICs. That's one of the reason superconductive technology is the prominent one [47] and has been selected by giants like IBM and Google for realization of their most advanced quantum computers [47]–[49] (both IBM and Google employ transmon qubist, which consist of capacitively shunted Josephson Junctions).

The most advanced superconductive based quantum computers offer more than 100 qubits (105 in case of Google's Willow [49]) and provide frameworks for Quantum Error Correction techniques which are required for progress in this field. As for the ion-trap technology, focus is put not solely on the number of qubits a single chip can host, but also on miniaturization and integration of as much of the accompanying control and readout logic as possible.

3) Semiconductor Quantum Dot based quantum computing: Quantum Dots is another promising platform for quantum computing, one gaining recently more and more interest as QDs offer excellent compatibility with semiconductor fabrication processes, including CMOS and III-V manufacturing technologies, enabling potential for event better miniaturization and greater integration than dominating ion-trap and superconductive solutions. What's also interesting, Quantum Dots allow realization of charge and spin qubits, offering greater flexibility and freedom when selecting optimal solution for a particular application [50], [51] (implementation of charge qubits is unlocked thanks to modern nanometer SOI processes [47]). CEA LETI is one of the most active institutions when it comes to QDs based qubits research. Researchers pursuit new architectures of qubit arrays, for higher fidelity and noise immunity, and integration of readout and control logic. CEA LETI characterized their SOI processes for cryogenic temperatures. The ultimate gola is of course increase in the number of qubits provided by the Qunatum Processor [52], [53].

C. Quantum Sensing Integrated Circuits

Quantum sensing IC usually implements both the sensing element (e.g. coil) and the required control and sensing electronics. Quantum sensing has already proven to outperform it's classical counterparts in applications like magnetoencephalography, gas sensing, temperature sensing [54].

The platform for quantum sensing is usually based on [47], [54]

1) Electron spin resonance (ESR);
2) Nuclear magnetic resonance (NMR);
3) Rydberg atoms (high excited stat);
4) Nitrogen Vacancy centers in diamonds.

An aggressively scaled down detectors realized in nanometer CMOS technologies can operate at frequencies of hundreds of GHz and provide enhanced sensitivities. Monolithic realization of control and detection logic minimizes parasitic components. Thanks to miniaturization, it's already possible to manufacture a portable NMR spectrometers [54].

D. Quantum Photonic Integrated Circuits

Quantum Photonic ICs provide a platform for miniaturization by enabling on-chip generation, processing, and detection of quantum state of photon (light) and as a result advance the pursuit of practical implementation of quantum network enabling reliable and secure quantum communication. A significant progress in the development of photonics quntum devices, mostly integrated, has been observed in the recent years [55]. Researchers demonstrated Quantum Key Distribution free-space link working over 2000km [56] or chip to chip teleportation [57], achievements only possible with the utilization of large scale integration. Any further advancement requires even more tight coupling and integration between key components of photonic quantum systems and investment into emerging photonic IC technology.

The ongoing researches cover photonic platform materials. The main challenge is to develop platform which can support with high efficacy all three key components i.e. quantum light sources, quantum high-speed modulators, and quantum photodetectors. On top on that the platform should provide efficient waveguide capabilities [55], [58]. The materials actively investigated for integrated photonics include [55]:

1) silica waveguides (silica-on-silicon and laser-written silica waveguides);
2) silicon-on-insulator (SOI);
3) silicon nitride (Si_3N_4);
4) gallium arsenide (GaAs);
5) indium phosphide (InP);
6) silicon oxynitride (SiO_xN_y).

While silicon derivatives offer potential for high density integration, also with control logic, thanks to compatibility with CMOS processes, they do not provide means for building integrated laser sources. This problem is solved when GaAs or InP platform is selected, but at much higher cost [55] and lower integration potential.

A great progress has been made in the scope of quantum light sources, which are key elements of quantum optical systems. Researchers can build single photon sources with satisfactory efficiency, indistinguishability and fidelity [55], [59]. Typically a Four-Wave Mixing base sources are utilized, however a lot of efforts is put into Quantum Dot single photon sourcing [59], especially ones compatible with CMOS (silicon) processes.

[55] lists recent achievements, these include:

1) InAs/GaAs self-assembled Quantum Dot single photon sources;
2) Silica on Silicon four-wave mixing (SFWM) heralded single-photon sources (HSPSs);
3) Spontaneous parametric down-conversion (SPDC) entangled photon source based on a LN photonic;
4) Silicon fabricated polarization splitter/rotator, thermo-optic phase shifter and Mach-Zehnder interferometer;
5) Directional coupler with a thin layer of $Ge_2Sb_2Te_5$ (GST);
6) Hybrid quantum photonic circuit integrated with an on-chip tunable ring resonator filter;
7) Ge-on-Si lateral single-photon avalanche photodiode;
8) NbN nanowire traveling wave SNSPD atop a silicon waveguide with detection efficiency up to 91%.

E. Summary

1) Advancements in quantum technologies, especially quantum computing and quantum communication, would have not been possible without modern integrated circuits fabrication technology;
2) The goal is to pursuit large scale integration and reuse as much as possible, especially from the commercially available CMOS processes;
3) Characterization for different application and environment requirements (e.g. cryo-temperatures) might be necessary for the reuse of processes established for manufacturing of classical applications;
4) A hybrid approach will be used whenever the efficiency and performance is of the greatest concern, for low cost applications, economically viable solutions will be adapted.

VII. Discussion, Conclusions

The convergence of Quantum Information Science and Technologies (QIT) with established disciplines in Information and Communication Technology (ICT) presents both formidable challenges and unprecedented opportunities. Our exploration, guided by the perspectives of diverse engineering students engaged in specialized research areas, has unveiled the intricate interplay between QIT and domains like biomedical engineering, electronics, software, communications, machine learning and cybersecurity.

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