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Overview of solutions in Quantum Information Technologies, part 1

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***Abstract*—The article presents an overview of the quantum technologies across diverse domains. The exploitation of quantum phenomena—such as superposition, entanglement, and quantum interference—allows the introduction of practical and sometimes still theoretical innovations in a wide range of technologies that at some point met an insuperable obstacle in their development. The first part of the series of articles focuses on the influence of quantum information technologies on cryptography, computational physics, hardware, digital electronics, machine learning and healthcare applications. The seven sub-articles address both the opportunities and challenges of deploying quantum technologies.**

***Keywords*—Quantum Technologies, Post-Quantum Cryptography, Quantum Monte Carlo, Quantum Cascade Lasers, Quantum-dot Cellular Automata, Quantum Metrology, Quantum Neural Networks, Quantum Signal Processing**

I. Introduction

THE emergence of quantum technologies introduced the solutions for the limitations met by classical technologies but also new challenges that humanity must overcome. All of that thanks to the exploitation of quantum phenomena: superposition, entaglement and quantum interference. The influence reaches a wide range of domains, from cryptography, through computational physics, to healthcare. The following seven subarticles create a first part of the roadmap of the innovations that emerged because of the breakthroughs in quantum information technologies.

Cryptography is an example of the domain that faced a new challenge in the quantume era. Shor's algorithm presented a thread to the entire current encryption schemes that kept the digital world secure and private. In response to that the post-quantum cryptography emerged.

Computational physics overcame its limitations, as Quantum Monte Carlo methods enabled precise solutions to many-body problems while addressing challenges like the fermionic sign problem through innovations such as Q2VMC and hybrid QC-QMC approaches.

Hardware gained new capabilities, with Quantum Cascade Lasers providing versatile radiation sources across MIR, FIR, THz, and NIR spectra, serving as tools for matter manipulation, information carriers in quantum communication, and potential generators of quantum states.

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Digital electronics found a promising alternative in Quantum-dot Cellular Automata, which offer lower power consumption, higher operating speeds, and further miniaturization beyond CMOS limitations.

Sensors achieved unprecedented precision with a quantum metrology, as NV centers in diamond enabled ultra-accurate magnetic field measurements at room temperature, revolutionizing applications in biology, materials science, and beyond.

Machine learning expanded its toolkit, with Quantum Neural Networks introducing hybrid architectures that combine quantum feature extraction with classical models to enhance tasks like speech recognition.

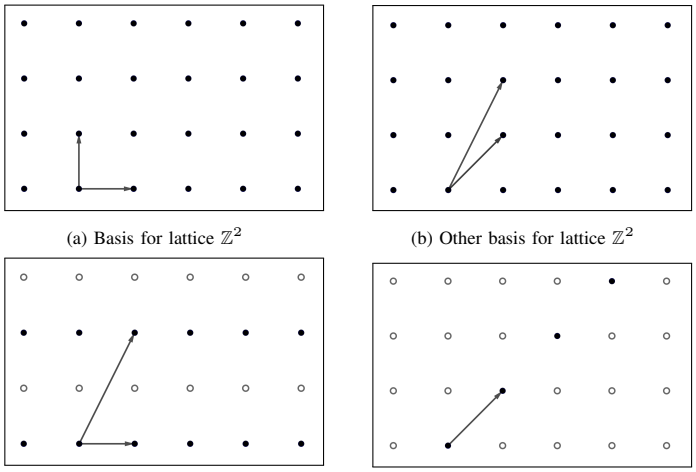
Healthcare addressed its data challenges, as Quantum Signal Processing and quantum machine learning overcame the limitations of classical filters in processing noisy mobile sensor data for digital phenotyping.

II. Post-Quantum Cryptography

For years, the basis of the world's cryptography (RSA, ElGamal, ECC, etc.), now called classical cryptography, relied on the security of problems defined on finite abelian groups. In the case of RSA and ElGamal, this is the multiplicative group modulo n. In 1996, Peter W. Shor introduced a probabilistic algorithm for quantum computers that, for a given abelian group of size n, can find the period of a function with stable probability in $polylog(n)$ time [1]. In other words, if a problem can be reduced to finding the period of some function, then with a sufficiently powerful quantum computer, we can easily solve it. We can break the cryptographic algorithms that secure our entire digital world.

A search for the solution began, creating a new field in cryptography called post-quantum cryptography. The idea was to find problems resistant to quantum computing capabilities. Currently, lattice-based problems are viewed as the most promising. Lattices are defined as discrete subgroups of $(\mathbb{R}^n, +)$. We can think of them as subsets of $\mathbb{R}^n$ described by a given set of vectors called a basis. For cryptographic purposes, only full-rank lattices are considered: the cardinality of the basis is equal to the dimension of the space for which the lattice is defined. The examples of lattices are shown in Fig. 1.

The foundation for considering lattice problems worth exploring was laid by Miklós Ajtai in 1996 [2]. He proved that



(a) Basis for lattice $\mathbb{Z}^2$

(b) Other basis for lattice $\mathbb{Z}^2$

(c) Basis for a lattice that is not $\mathbb{Z}^2$

(d) a not full-rank lattice

Fig. 1. Examples of lattices and their bases

lattice-based problems are average-case hard, not only worst-case hard. This means that if we choose random instances of these problems, they cannot be easily solved by heuristics. In other words, Miklós Ajtai provided mathematical proof of the following claim: if there exists an efficient algorithm for the average-case lattice problem, then there must be an efficient algorithm for the worst-case version of the same lattice problem. This is one of the core properties that problems must fulfill to be useful in the field of cryptography.

The final steps were made by Oded Regev. First, in 2003, he showed that lattice-based problems can be reduced to the Hidden Subgroup Problem for non-abelian groups—that means they are resistant to Shor's algorithm [3]. Lattice-based problems hit the sweet spot of cryptography: they are now believed to be secure for use in cryptography because we do not know of any quantum algorithm that outperforms classical algorithms for these problems.

Next, in 2009, Regev introduced the Learning With Errors (LWE) problem and proved that solving average-case instances of LWE is equivalent to solving worst-case instances of lattice-based problems [4]. Over the years, his idea was optimized in terms of cryptographic key sizes and computational efficiency, leading to the development of practical cryptographic solutions and the publication of the official NIST standard in 2024 [5].

The LWE problem in its elementary form is defined as follows: we are given an n-dimensional space and a modulus $q = poly(n)$. Let χ be the error distribution from which we draw the noise. Then $\mathbb{Z}_q^n$ is the set of integer vectors of dimension n in the world modulo q. An instance of the problem consists of a secret vector $s \in \mathbb{Z}_q^n$ and input data: vectors $A = a_1, a_2, \ldots, a_m \in \mathbb{Z}_q^n$ and values $B = b_1, b_2, \ldots, b_m$ defined as:

$$b_i = \langle s, a_i \rangle + \varepsilon_i,$$

where $b_i \in \mathbb{Z}_q$ and $\varepsilon_i \in \chi$.

Without the noise in the values B, the problem would be simple. We have efficient algorithms that allow us to find the secret vector s on classical computers. The noise makes it necessary to first find the 'correct' values B' to retrieve the secret s.

This means that breaking a cryptographic algorithm based on the LWE problem requires solving a lattice-based problem called the Closest Vector Problem (CVP): given a lattice L with basis B and a point $t \in \mathbb{R}^n$, find the point that belongs to the lattice and is closest to t.

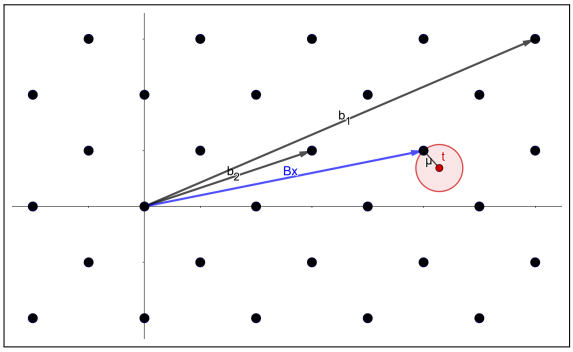


Fig. 2. Example instance of CVP

Let us consider a simplified example of the use of LWE in cryptography.

Private key: the secret s.
Public key: pairs of equations (A, B).
Let q be a prime number, and the secret s:

$$(s_1, s_2, s_3)$$

vectors A:

$$\begin{aligned} &a_{1,1}x + a_{1,2}y + a_{1,3}z \\ &a_{2,1}x + a_{2,2}y + a_{2,3}z \\ &a_{3,1}x + a_{3,2}y + a_{3,3}z \\ &\ldots \end{aligned}$$

noise E:

$$\begin{aligned} &\varepsilon_1 \\ &\varepsilon_2 \\ &\varepsilon_3 \\ &\ldots \end{aligned}$$

Then for every i, we create equations $b'_i = \langle s, a_i \rangle$:

$$\begin{aligned} a_{1,1}x + a_{1,2}y + a_{1,3}z &= a_{1,1} \cdot s_1 + a_{1,2} \cdot s_2 + a_{1,3} \cdot s_3 = b'_1 \\ a_{2,1}x + a_{2,2}y + a_{2,3}z &= a_{2,1} \cdot s_1 + a_{2,2} \cdot s_2 + a_{2,3} \cdot s_3 = b'_2 \\ a_{3,1}x + a_{3,2}y + a_{3,3}z &= a_{3,1} \cdot s_1 + a_{3,2} \cdot s_2 + a_{3,3} \cdot s_3 = b'_3 \\ &\ldots \end{aligned}$$

Next, we add the noise from distribution χ:

$$\begin{aligned} b'_1 + \varepsilon_1 &= b_1 \\ b'_2 + \varepsilon_2 &= b_2 \\ b'_3 + \varepsilon_3 &= b_3 \\ &\ldots \end{aligned}$$

The last step is to apply modulo q to the equations, and then the public key is as follows:

$$(a_{1,1}x + a_{1,2}y + a_{1,3}z,\ b_1)$$
$$(a_{2,1}x + a_{2,2}y + a_{2,3}z,\ b_2)$$
$$(a_{3,1}x + a_{3,2}y + a_{3,3}z,\ b_3)$$
$$\dots$$

Bob wants to send a single encrypted bit to Alice. He chooses a linear combination of equations from the public key and creates a new equation:

$$\begin{array}{rrrrrrr} & a_{1,1}x & + & a_{1,2}y & + & a_{1,3}z & = b_1 \\ + & a_{3,1}x & + & a_{3,2}y & + & a_{3,3}z & = b_3 \\ \hline & a_{Bob_1}x & + & a_{Bob_2}y & + & a_{Bob_3}z & = b_{Bob} \end{array}$$

Next, Bob encrypts the bit. If the bit is '0',

$$b_{Bob} + 0$$

if the bit is '1',

$$b_{Bob} + \frac{q-1}{2}$$

Why $\frac{q-1}{2}$? It is the value furthest from '0' in the world modulo q. It will prove useful during decryption of the bit.

Bob wants to encrypt the bit '1'. Then he must send to Alice:

$$(a_{Bob_1}x + a_{Bob_2}y + a_{Bob_3}z\ ,\ b_{Bob} + \frac{q-1}{2}).$$

Alice decrypts the message. She calculates the 'correct' (noise-free) result for the equation sent to her by Bob—Alice has the secret s, so this is easy for her.

$$s \cdot (a_{Bob_1}x + a_{Bob_2}y + a_{Bob_3}z) = b'_{Bob}$$

Now Alice can retrieve the bit encrypted by Bob. She just needs to calculate the difference between the 'correct' result and the result sent to her by Bob—his result has noise because of the noise added to the public key. If the difference is closer to 0, then the encoded bit was '0'. Otherwise, if the difference is closer to $\frac{q-1}{2}$, the encoded bit was '1'.

$b'_{Bob} - (b_{Bob} + \frac{q-1}{2}) \approx \frac{q-1}{2} \rightarrow$ closer to $\frac{q-1}{2}$ so the bit was '1'.

The NIST standard [5] introduced computational optimizations to the above algorithm:

- use of vectors of polynomials in place of scalars, encoding more information in a single exchange
- additional noise after Bob encodes bits
- compression and decompression of messages during exchange and storage
- use of the Fujisaki-Okamoto transformation for improved polynomial multiplication

Cryptography is a field that requires continuous work and improvements to respond to advances in technology. The security of cryptographic schemes is based on the assumption that efficient algorithms for certain problems do not exist—until the moment they do. There is a chance that the day will come for post-quantum cryptography algorithms as well. Then the search for the next generation of cryptography will begin again.

III. Quantum Monte Carlo [6]–[8]

Solving many-body problems in quantum physics — in particular, the quest to find an exact solution to the Schrödinger equation — is one of the greatest computational challenges facing modern science. Quantum Monte Carlo (QMC) allows this problem to be solved. It uses stochastic sampling of particle configurations, evaluates the probability of their occurrence, and simulates their evolution in imaginary time to determine the ground-state energy with high precision while avoiding direct manipulation of complex mathematical models.

The basic classification of QMC methods includes variational and diffusion approaches. Both methods are used to determine the ground state but differ significantly in their underlying mechanics.

Variational Quantum Monte Carlo (VMC) assumes that the shape of the wave function is roughly known, but its exact parameters are unknown. This method is based on the use of a parameterized wave function. The algorithm calculates the energy of the entire sampled system based on specified parameters, and the resulting energy is always greater than or equal to the actual ground-state energy. The process then enters a mode of iterative optimization of these parameters to minimize the result. VMC requires relatively little computational power, but its disadvantage is its almost complete dependence on the mathematical quality of the trial function entered by the user.

Diffusive Quantum Monte Carlo (DMC) assumes that the Schrödinger equation, after transformation into a virtual time function, can be replaced by a diffusion equation. This approach is based on a mathematical transformation of the Schrödinger equation into imaginary time. In this framework, the equation takes the form of a combination of the diffusion equation and the rate equation. In subsequent iterations, the positions of randomly selected particles are modified, and the new configurations are assigned a specific "weight" dependent on the reference energy. Instead of optimizing rigid parameters as in VMC, the DMC method simulates "time evolution," seeking the natural stabilization of the system at the lowest possible energy. This provides nearly perfect accuracy and eliminates the influence of human error in function selection, but has the drawback of high processor power requirements.

Despite their great potential, QMC methods face three key challenges: the fermionic sign problem, high computational cost, and dependence on the quality of the trial function. The fermionic sign problem is the most troublesome of these. It manifests itself during stochastic evolution, where the weights of individual statistical samples alternate between positive and negative signs. This leads to the need to average a sample pool that grows exponentially with the size of the system. Traditional methods used to date to circumvent this problem rely on imposing artificial constraints, which allow for high performance but can potentially lead to very serious systematic errors due to the limited flexibility of the classical test function used.

To address emerging challenges, new QMC methods are being developed. Their goal is to achieve the best possible results at the lowest possible cost and to find a way to deal with the fermionic sign problem.

Quadratic Quantum Variational Monte Carlo (Q2VMC) is an innovative extension of the standard VMC algorithm, in which the key change is the mathematical addition of a quadratic term to the update coefficient. Instead of optimizing only rigid parameters, Q2VMC performs a discrete evolution directly in Hilbert space and then projects it onto the parameter space. This results in a twofold increase in optimization speed, greater accuracy for complex particle systems, and improved process stability, without any additional computational costs.

Quantum-Classical QMC (QC-QMC) is a groundbreaking hybrid method based on the division of labor between a traditional supercomputer and a quantum processor during the phase of imposing constraints to address the fermionic sign problem. Instead of creating an imperfect trial function on a classical computer, the algorithm uses an advanced quantum processor as a coprocessor to generate far more versatile quantum trial functions that cannot be replicated using traditional methods. Before a classical computer performs the bulk of the calculations in imaginary time, a quantum system using a technique called "shadow tomography" instantly measures the random values of the superposition of states against a reference model. It reduces systematic error and allows for the precise elimination of statistical errors without an exponential increase in the required sampling time.

Due to their ability to accurately predict chemical kinetics and reactivity, these methods have a wide range of practical applications, ranging from quantum chemistry to materials engineering, and on to nuclear physics and astrophysics. QC-QMC was used in several experiments. For example, in the field of quantum chemistry, experiments have been performed on the breaking of bonds in the hydrogen (H4) molecule and the stretching of nitrogen (N2). The bond-breaking of the H4 molecule was performed using 8 qubits. The four-hydrogen-atom system is known for its degenerate states, which classical "gold standards" of quantum chemistry (such as the CCSD(T) model, which can be off by as much as several dozen kcal/mol) cannot handle. QC-AFQMC, by incorporating the powerful concept of virtual spatial correlation spanning as many as 120 orbitals, brought the result close to the highly stringent threshold of chemical accuracy (errors less than 1 kcal/mol), while perfectly handling the inherent noise of quantum devices. The stretching of the N2 bond was performed on 12 qubits. By examining a space of up to 60 orbitals, it was demonstrated that as the nitrogen bond stretches, the classical AFQMC method tends to be off by -8 kcal/mol, while the super-accurate classical CCSD(T) method is off by as much as 14 kcal/mol. The hybrid variant (QC-AFQMC) drastically reduced the error range to between -2 and 1 kcal/mol. The QC-QMC algorithm has also found applications in materials engineering. The experiment investigated a diamond crystal. Conducted on a powerful 16-qubit array, the experiment focused on the unit cell lattice of a solid diamond, consisting of 2 atoms and 26 orbitals. It demonstrated the invaluable utility of the method for simulating complex periodic materials. This is the largest chemical simulation ever performed on a physical quantum computer, with results that matched the accuracy of established classical methods despite the use of a simple quantum trial function.

Quantum Monte Carlo (QMC) methods are currently among the most precise computational tools available for determining the ground-state energy of quantum systems. Although their primary purpose is to solve complex problems involving many-body systems, they are equally effective for single particles.

Although the classical variants of these algorithms (VMC and DMC) have faced significant obstacles over the years—namely, the fermionic sign problem, high computational costs, and dependence on the quality of the trial function—the development of modern variants marks an absolute turning point. Innovations such as mathematically refined Q2VMC algorithms or hybrid QC-QMC methods, which combine classical computations with the capabilities of quantum processors, allow for the effective elimination of previous limitations and systematic biases.

IV. Quantum Cascade Lasers as Functional Components of Quantum-enabled Systems Requiring MIR, FIR and THz Radiation

To deliver its promised advantages, quantum technology needs to harness matter and phenomena of our physical world with unmatched excellence. This often means constructing sophisticated systems made of functional building blocks. It also happens that investigating the principles of operation and engineering aspects of some of those more elementary devices is an intricate endeavor in its own right. One of such inventions is a quantum cascade laser (QCL). While this device finds its use in many applications, in this short article, the author wishes to present several interesting solutions related to quantum technology emphasizing particle control and quantum information, in which a QCL has either been implemented, or could have been in principle. The aim is to provide an interdisciplinary inquiry about cases from various corners of quantum technology and nanotechnology. The examples are assigned one of two categories—QCL beam as a tool or as an information carrier. There is also a third category, QCL as quantum state generator, but, at least for now, this listing is of more speculative nature.

The device being discussed here is itself, as the name suggests, a direct result of utilizing quantum phenomena. For a detailed study of the physical description of QCLs, the reader is referred to the book by Jérôme Faist [9], whose research team built the first working instance of the device in 1994 [10]. The concept, broadly speaking, is a laser in which optical gain is achieved across a heterostructure made of alternating layers of at least two materials, whereas one is the well and the other—the barrier material. Clever selection of thicknesses of these layers results in a series of coupled quantum wells, a superlattice structure. Electronic states in such superlattice are confined with discrete energy levels grouped into subbands. Electrons can undergo intersubband transitions, emitting photons in the process while the phenomena of quantum tunneling and longitudinal optical electron-phonon scattering maintain population inversion. The structure is designed to form a stream of "cascading" electrons when electrical polarization is applied across it, resulting in laser action. Since its first realization, this technology has been continually developed

to become one of the most versatile family of coherent electromagnetic radiation sources [11]. In the present day, QCLs can generate frequencies from a very wide spectral range: mid-infrared (MIR) [12], far infrared (FIR) [13] as well as terahertz (THz)—a part of the spectrum which could not have been easily accessed for a long time (the "terahertz gap") [14], [15]—and it is also worth noting, near-infrared (NIR) generation is also being pursued [16]. They can operate in CW and pulsed mode [17], or, what is especially interesting for quantum computing and metrology, can generate optical frequency combs [15], [18]–[21]. As semiconductor devices, they are also integrated as part of photonic chips [22]. According to source [20], QCLs can naturally exhibit narrow linewidths limited by quantum fluctuations (intrinsic linewidths) and high spectral purity. Moreover, their parameters can be further improved by implementing frequency stabilization and phase locking. Desirable parameters, spectral variety and integration possibilities make these devices a powerful tool suiting diverse needs.

Laser Beam as a Tool: This category captures solutions where the laser beam is not meant to be the main information carrier, but rather an instrument for: manipulation of matter, energy delivery, excitation or sampling of quantum states. In this context, the most prevalent QCL properties that could be exploited are the capability of generating a specific wavelength and controlled power transfer. The first example is an interesting study from 2016 in which simulation was used to investigate the possibility of optically tweezing dielectric nanoparticles [23]. The method uses a doped graphene plane with round nanoaperture. When illuminated with appropriate wavelength MIR beam, localized surface plasmons are excited, and the arising gradient of optical forces pulls a particle toward the aperture—tweezing effect. Another idea involves time-domain terahertz spectroscopy for probing optically tweezed molecules by Rhie and others [24]. This one used optical tweezers working in optical wavelengths and a Ti:sapphire laser for excitation via ultrashort pulses—signal detection is done with a nanoantenna fabricated with photolithography. These advances could become useful in chemo- and biosensing. A QCL designed to generate MIR or ultrashort pulses could not only fit the functional requirements for those two presented experiments, but also, with its integration possibilities, allow for a more industry-accessible lab-on-a-chip system. Another source describes using QCL beam in THz range for nanoscopic measurements of a nanowire to examine its electrical and optical properties. An older paper from 2008 [25] provides a framework for realization of physical qubits with rovibrational wave packets in carbon monoxide and nitric oxide, the state of which could be manipulated with MIR pulses [26]. The authors did not specify what source could be used. Knowing there is a limited number of sources in this regime, one could make an attempt to verify this model experimentally using the QCL in pulsed mode with spectral content tuned to match what is demanded by the theory.

Laser Beam as an Information Carrier: Here, we consider situations where the laser beam encodes quantum information. It may, therefore serve as a qubit or qudit in some cases. The first example in this category is a practical realization of a free-space private optical communication channel using a QCL [27]. Transmission was done in MIR, and remarkably its scheme had exploited chaotic behavior of lasers to improve the security of sent data. Many times the term "beam" has to actually be reevaluated since many times a more exotic state of light is used—a frequency comb [28]. QCLs can be made to work in this regime with the phenomenon of four-wave mixing [15]. Frequency combs possess interesting properties regarding their time-frequency representation, and can consequently be used for quantum computation. Publication by Reimer and others [19] presents a set of procedures to photon pairs, entangled photon pairs and multi-photon entangled states that spectrally span wide frequency combs. Sources [29], [30] discuss generation of: multiphoton time-bin entangled states, frequency-entangled photon pairs and optical qudit clusters. Those techniques involve time- and frequency-bin processing that define in which space the entanglement is resolved [31], [32]. A team from Japan [33] proposed a scheme for linear optical quantum computation. Here, a single-photon frequency comb plays the role of a qubit, and its time-frequency degree of freedom is operated on. Authors of those publications were not explicit about what light sources were used or could have been used (theoretical works) in their setups. Once again, it is reasonable to suspect QCLs could be implemented in the discussed schemes as they can exhibit four-wave mixing—phenomenon that generates frequency combs and is further taken advantage of for entanglement, and their parameters are well suited for low-noise and consistent measurements. What is more, integration capabilities open up perspectives for novel on-chip quantum state generators.

Laser as a Quantum State Generator: This category's purpose is to posit questions and perhaps spark a conversation—can the structure of a QCL be leveraged to obtain quantum states more directly? Rather than merely using its beam for manipulation or modifying it as it passes through some external system? Perhaps a paper from 2022 [34] may be our initial clue. Its authors demonstrate a QCL design for two-photon emission in THz range. The well structure of this device was chosen in such way that electron emits two photons when undergoing a transition from upper to lower energy eigenstate in a resonant process. This particular design is supposed to work similarly to a regular QCL, but naturally, a question arises if the process generates pairs of entangled photons. The article states, this is expected provided non-resonant two-photon transitions occur instead. Two years later, the next step was made, and a non-resonant two-photon transition was achieved in a QCL as reported in source [35]. Here, the researchers also appreciated the potential for achieving entangled photon generation but had not examined their physical device from this angle.

In summary, applications of QCLs were segregated into three categories to highlight their role in a particular quantum-enabled device. Examples were chosen from different fields to illustrate the interdisciplinary nature of quantum research and involved the subjects of: optical tweezers, physical qubit manipulation, nanoscopy, frequency combs as qubits and entangled photon generation. The list is by no means exhaustive. The author wishes to underline that in many publications,

reporting usage of electromagnetic radiation for a specific purpose, detailed information about its source is not provided. Because of this, this text reports not only literature findings but also suggestions for future inquiry.

V. Quantum DSP

Complementary Metal Oxide Semiconductor (CMOS) technology is approaching its physical limits, which encourages researchers to explore new solutions in the field of digital circuit design. One promising approach is *Quantum-dot Cellular Automata* (QCA), first introduced in 1993 [36]. In recent years, interest in this technology has grown significantly, along with new concepts for its application in digital systems.

In contrast to CMOS, which relies on electric current flow, QCA operates by manipulating electron charge. This approach provides several important advantages, including lower power consumption, higher operating speed, and the potential for further miniaturization [37]. However, the technology is still largely in the simulation phase, making research in this area highly relevant and open.

This article presents the structure and operating principles of QCA, and discusses possible implementations of selected logic circuits. Simulation results are also presented and compared with their counterparts implemented in CMOS technology.

The fundamental element of QCA is a cell consisting of four quantum wells arranged in a square and two electrons, as shown in Fig. 3. According to Coulomb's law, electrons tend to occupy positions as far apart as possible, resulting in two possible polarizations denoted as $P = +1$ and $P = -1$, corresponding to logical states "1" and "0", respectively.

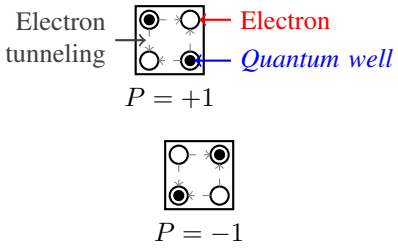


Fig. 3. Structure of a QCA cell: two possible polarizations ($P = +1$ denotes logical 1, $P = -1$ denotes logical 0). Electrons (black circles) occupy quantum wells and can move between them via the tunneling phenomenon (gray arrows).

Electrons can change their positions only within a cell through the tunneling phenomenon. They cannot move between cells.

In conventional approaches, information transfer is associated with current flow. In QCA, it is still governed by Coulomb interactions. Fig. 4 shows information propagation between cells. As mentioned earlier, electrons tend to maximize their distance, so when one cell becomes polarized, neighbouring cells are polarized accordingly.

Another essential element of QCA operation is the clock. As shown in Fig. 5, the clock is divided into four zones, each shifted by 90°. The phases are:

- *Switch* – Potential barriers increase, and the cell begins to polarize.

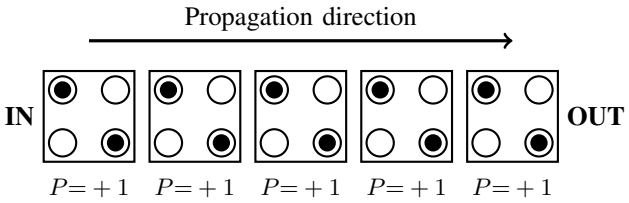


Fig. 4. Information transmission in a line of QCA cells. The polarization of the input cell (IN) induces successive cells through electrostatic interactions.

- *Hold* – Barriers reach maximum value, and polarization is maintained.
- *Release* – Barriers decrease, and the cell loses polarization.
- *Relax* – Barriers reach minimum, and the cell is in a depolarized (superposition) state.

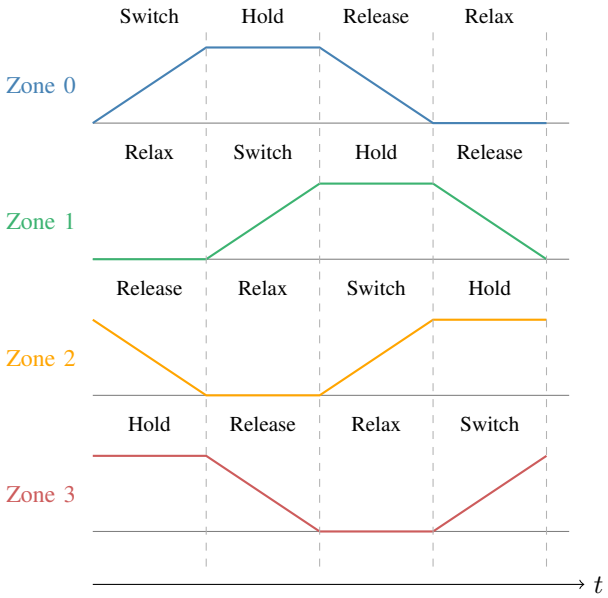


Fig. 5. Four QCA clocking zones within a single cycle. Each successive zone is shifted by one phase: *Switch*, *Hold*, *Release*, *Relax*.

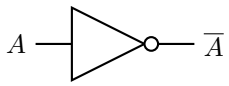
The clock is responsible not only for data propagation but also acts as a power supply. The rising phase provides energy for increasing and maintaining potential barriers. As a result, energy consumption is very low, since the clock is the only energy-consuming component.

Fig. 6 shows a basic NOT gate and its implementation in QCA [38]. This gate inverts the input signal.

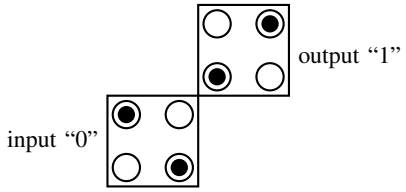
Fig. 7 presents the majority gate. It has three inputs (A, B, C) and one output, which takes the dominant logical value among the inputs.

Based on these basic gates, more advanced blocks such as *Configurable Logic Block* (CLB), *Look-up Table* (LUT), *Static Random Access Memory* (SRAM), and *Arithmetic Logic Unit* (ALU) can be constructed. Detailed designs are presented in [39], [40]. These structures are significantly more complex, and ongoing research focuses on reducing the number of cells while maintaining performance.

Comparisons of area, energy consumption, and operation time show that QCA reduces energy consumption by approx-



(a) NOT gate symbol



(b) QCA implementation

Fig. 6. NOT gate: (a) classical logic symbol, (b) implementation in QCA technology.

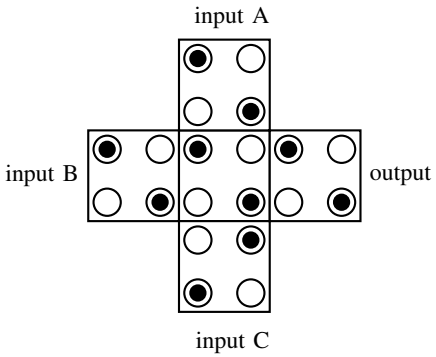


Fig. 7. *Majority gate* implementation in QCA

imately six orders of magnitude, improves speed by three orders of magnitude, and enables nanometre-scale implementations compared to CMOS [41].

This article presented the structure and operation of QCA as an alternative to widely used CMOS technology. The analysis and simulations indicate that QCA offers significant advantages in key aspects of digital circuit design.

In terms of energy consumption, QCA has a clear advantage—electron charge manipulation, instead of current flow, drastically reduces energy losses. The technology also enables higher operating speeds and further miniaturization beyond the limits of current lithography used in CMOS.

Although QCA is still in the simulation stage, rapid progress in this field is promising. It has real potential to replace CMOS and define a new direction for digital electronics.

VI. Quantum Metrology of Magnetic Materials: NV Centers in Diamond

The development of quantum sensors has ushered in a new era of measurement precision [42]. These sensors utilize the laws of quantum mechanics to achieve extraordinary accuracy, outperforming classical sensors. By taking advantage of quantum superposition, entanglement, and highly sensitive spins, they are actively breaking the barriers of traditional scientific methods. A leading example of this technological leap is the quantum metrology of magnetic materials utilizing NV centers in diamond.

The core of this quantum sensing technology is the Nitrogen-Vacancy (NV) center, which is often described as the perfect "defect" within a crystal. Structurally, it occurs in a diamond lattice when a nitrogen (N) atom replaces a regular carbon atom, and the adjacent spot in the lattice remains a vacancy (V), or an empty space. Together, this specific atomic configuration creates a system that exhibits unique magnetic properties, primarily defined by its spin.

Within this NV center, electrons possess a fundamental quantum characteristic known as spin. This spin effectively operates like an atomic compass needle. Because of this property, the spin reacts strongly to external magnetic fields. The application of a magnetic field subsequently alters the energy levels of these electrons, creating a measurable quantum response.

The operational principle of an NV center sensor is based on optical excitation and the detection of emitted light. The process relies on the use of a green laser to excite the NV center. Following this excitation, the diamond emits a red light through a process called fluorescence. Crucially, when a magnetic field is present in the environment, the brightness of this fluorescent red light visibly decreases.

To capture and analyze this phenomenon, a specialized measurement apparatus is employed. The standard setup consists of three primary components:

- **A laser:** This serves as the primary source of excitation for the NV center.
- **A microwave generator:** This is used to deliberately manipulate the quantum spin of the system.
- **An optical detector:** This component precisely measures the brightness of the emitted fluorescence.

A prominent example demonstrating the power of this technology is the measurement of magnetic fields within biological samples, such as a nerve cell. The method requires placing NV centers embedded within a diamond very close to the target sample.

The measurement follows a specific sequence of actions:

1) The process begins by illuminating the NV centers with a laser to cause excitation and fluorescence.
2) Next, a scanning microwave signal is applied to the sample.
3) The researchers then observe a drop in the brightness of the fluorescence when the microwave frequency hits resonance.

The ultimate result of this methodology is the successful reconstruction of a magnetic field map possessing nanometer resolution [43]. The practical applications of this process are highly impactful; it allows scientists to study electrical currents within individual neurons, investigate the magnetism of bacteria, and measure the magnetic fields of single molecules [44].

Diamond is uniquely suited for these advanced quantum measurements. One of its most significant advantages is that the sensors can function efficiently at room temperature [45]. Furthermore, diamond features high biocompatibility, making

it entirely safe for use with delicate biological tissues. Finally, this platform provides an exceptionally high degree of sensitivity and spatial resolution [46].

The inherent versatility of NV center sensors enables a vast array of practical applications. Beyond tracking magnetic fields, they are highly capable of precisely measuring other critical parameters like temperature and mechanical strain. Their uses span across general technology and scientific research, navigation and geophysics, as well as the biomedical field. Looking ahead, they are expected to be heavily utilized in laboratories, environmental studies, industrial applications, and broader future technologies.

This technology currently resides in a phase of dynamic development. Innovation is heavily driven by leading global research centers, including Harvard, MIT, and the University of Stuttgart. Concurrently, commercial companies such as Qnami, Element Six, and QDTI are actively developing these systems for the market. The future of NV sensors holds great promise, as they are consistently setting entirely new standards for precision.

In summary, the use of NV centers in diamond for quantum metrology represents a powerful intersection of advanced fields: quantum physics, materials engineering, and modern measurement systems. By leveraging the nitrogen-vacancy defects as a sensor, researchers gain access to a tool with compact dimensions that functions perfectly at room temperature. This stands as a remarkable conclusion: it is a definitive example of how quantum phenomena can be practically utilized in the macroscopic world.

VII. Quantum Neural Networks

Neural networks are now a fundamental tool for acoustic signal analysis. Their advantage over classical methods lies in their ability to learn representations without manual feature engineering, which is particularly important in tasks such as speech recognition, speaker identification, and transcription of recordings. At the same time, there is growing interest in whether similar benefits can be achieved by combining classical models with quantum computing.

In audio processing, time-frequency representations are most commonly used, especially mel-spectrograms and MFCCs. In the analyzed approach [47], a sample x_i is mapped to a feature vector u_i in the form of a mel-spectrogram with dimensions

$$u_i \in \mathbb{R}^{60\times 1024}.$$

Such a representation facilitates the extraction of patterns relevant to automatic speech recognition (ASR).

In the ASR system, the quantum layer acts as a feature extractor, while the classical component is responsible for final sequence modeling and the classification decision [47]. The pipeline proceeds as follows: the audio signal is transformed into a mel-spectrogram, then divided into small patches, for example 2×2, which are encoded into quantum states. After passing through a variational quantum circuit (VQC) and measurement, `quanv` features are obtained and then passed to a local RNN/DNN model.

This architecture fits well within the federated paradigm: raw data remain on the client side, while only processed representations or parameters are exchanged between parties. From the perspective of voice-based applications, this is important because it reduces the risk of disclosing sensitive information.

The results reported in [47] suggest that the hybrid approach may improve the quality of speech recognition: the Quanv + RNNUAtt variant achieved 95.12% accuracy compared with 94.21% for the baseline RNNAtt variant. The potential benefits therefore concern both the quality of the extracted features and the effectiveness of the final classification.

At the same time, interpretative caution is needed. NISQ systems are susceptible to noise, and training quantum layers can be unstable and computationally expensive. For this reason, transfer learning becomes a practical strategy: first, a classical model is trained, and then selected layers are replaced with their quantum counterparts and fine-tuned [48]. Such an approach may improve stability and shorten training time.

Quantum neural networks do not currently replace classical ASR methods, but they constitute a promising extension of the feature extraction pipeline. The greatest potential of this technology currently lies in hybrid models that combine mature deep learning tools with experimental quantum components. Further progress will depend on the development of NISQ hardware, noise reduction methods, and more reproducible training procedures for classical–quantum models.

VIII. Quantum Signal Processing and Filtering of Noisy Data from Mobile Sensors for Digital Phenotyping

Digital phenotyping leverages continuous, passive data acquisition from mobile sensors to establish objective behavioral biomarkers, effectively mitigating the cognitive recall bias often present in patient reporting [49]. However, the progression of this field is severely constrained by the ”dirty data” bottleneck. Traditional Micro-Electro-Mechanical Systems (MEMS) sensors suffer from intrinsic thermal noise and calibration vulnerabilities. Furthermore, system-level power-saving protocols introduce arbitrary fragmentation and gaps into the recorded data streams. When classical linear filters are applied to these chaotic, highly non-linear human behavioral signals, they inevitably smooth out critical temporal dynamics and introduce phase lag, fundamentally failing to capture the true complexity of a patient's psychomotor state.

To overcome these classical limitations, Quantum Signal Processing (QSP) and emerging quantum hardware offer a transformative paradigm. By representing classical data as quantum states, algorithms such as the Quantum Extended Kalman Filter (QEKF) utilize quantum interference to drastically suppress noise and amplify weak target signals [50], [51]. Once the data is filtered, Quantum Machine Learning (QML) can map these complex time-series into high-dimensional Hilbert spaces, extracting deep, non-linear correlations in speech or gait that remain invisible to classical feature engineering [52], [53]. To eliminate hardware noise at the source, future mobile devices could transition from MEMS to quantum sensors, such as Nitrogen-Vacancy (NV) centers in diamonds

[44]. Because these tasks require offloading sensitive medical data to remote cloud Quantum Processing Units (QPUs), Quantum Key Distribution (QKD) is essential to provide a physically secure cryptographic framework [54].

Despite this profound theoretical potential, the practical deployment of quantum-enhanced digital phenotyping is heavily restricted by the realities of the Noisy Intermediate-Scale Quantum (NISQ) era [55]. Contemporary quantum processors are inherently prone to error and suffer from short decoherence times, which severely limits the depth and reliability of real-time algorithmic processing. Additionally, the physical miniaturization of quantum sensors—which currently require complex control optics or specialized thermal environments—presents a formidable engineering challenge for integration into ubiquitous smartphones and wearables. Nevertheless, as hardware matures, hybrid architectures combining classical mobile front-ends with secure quantum cloud backends are poised to revolutionize the precision and reliability of digital biomarkers in modern healthcare.

IX. Conclusion

All seven sub-articles show the undeniable influence of quantum technologies on the innovations and development in the wide range of fields—and they cover just a small part of them. As much as the quantum era enables overcoming numerous classical technologies' limitations, it introduces new obstacles and challenges as well. The use of quantum solutions is a subject of ongoing research and commercialization efforts with the promise of becoming a crucial part of the future of technology. This article serves as the first part of a series, providing a roadmap to further innovations in quantum technologies.

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