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Students' View of Quantum Information Technologies

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***Abstract*—The article is a sort of advanced publication workshop prepared by a group of M.Sc. students in ICT participating in the course on QIT. The idea behind the publishing exercise is to try to link, if possible, individual own work just under realization for the thesis with new unique possibilities offered by the QIT. Each chapter is written by a single author defining concisely her/his research interest in the classical ICT field and trying to find possible correlations with respective abruptly developing branches of the QIT. The chapter texts are somehow moderated by the tutor but are exclusively authored by young researchers. The aim was to present their views on the possible development directions of particular subfields of QIT, if not fully mature, but still based on their own ideas, research and dreams.**

***Keywords*—ICT; QIT; biomedical engineering; electronics engineering; sensors; quantum Internet; quantum computing**

I. INTRODUCTION

QUANTUM Information Technologies QIT are developing very fast, mainly in three directions indicated by the research and innovative industry – sensors, metrology and timing, computing and communications. Some quantum products from these areas are already available on the market, like first generation QKD, Q inertial navigation, variety of Q sensors, NISQ processors, simple Q networks, etc. However, due to a variety of involved material technologies, construction platforms, and application requirements, the promising QIT products have very different TRLs, ranging from commercial availability to early stages of development.

The European Quantum Flagship program EQF [1] was established in parallel to the similar actions undertaken by other global leaders in QIT, like the National Quantum Initiative in the USA [2], and massive quantum governmental initiatives in China. One of the products of the EQF is the European Strategic Research and Industry Agenda ESRIA [3]. Basing on the current QIT knowledge and cautious assessments of future technology developments, the SRIA combines three fields of existing assets and views of their representatives – directly QIT research and industrial communities, as well as relevant related R&D and industrial initiatives like EuroQCI (quantum communications), EuroQCS (quantum computing), EuroHPC (high performance computing), Euro Chips Act (semiconductor technologies and applications), European Strategy on Quantum Photonics and Photonics21 – A Key Enabling Technology for Europe. SRIA includes strongly justified views on balanced QIT developments all over Europe and recommendations in three mentioned technological pillars, emphasizing the need for simultaneous building relevant social and civilization layers.

Table I summarizes the recommendations emphasized in SRIA.

TABLE I
QIT 2030 – QUANTUM COMPUTING AND SIMULATION

Components	Development issues
Qubits	increase number, quality, interconnectivity, modalities
Qubit control	control of large number of entangled qubits
QOS and Compilers	quantum error correction, integration of NISQ with HPC
Q APIs and Cloud	global availability of Q hardware in cloud
Q Algorithms	identify and implement quantum advantage
User Community	provide massive access to academia, industry, SMEs over Q cloud
QS: digital, analog, heuristic	demonstrate quantum advantage, quantum-classical hybrid architectures
Quantum Communications	
Q photon sources	single qubit efficiency, wavelength and bandwidth requirements, photon purity
Q photon detectors	single photon regime, digital and continuous variable Q systems
Q memories	efficient Q interfacing between Q carriers, Q storage, and Q information processors
Q repeaters	long distance entanglement over fiber
Satellite network	efficient distribution of quantum resources – entanglement, contextuality
Optical fiber network	Q LAN and MAN, local net of Q resources
Q end nodes	Q interfaces to laptops and cell phones, towards the Q Internet
QC performance	increase bit rates, fidelities, link distance, robustness
QC integration	quantum-classical communications infrastructures
QC industrialization	affordable realization of civilization values, wide spectrum of functionalities
Quantum Sensing, Metrology and Timing	
Q metamaterials	application oriented tailored materials and Q-enhanced sensor technologies
QS algorithms	usage of non-classical states, absence of classical noise processes, protection from thermodynamic environment
QS control	identification of all Q degrees of freedom involved in measurements, contextuality
Q transducer	selective change of Q state of the probe
QS limitations	long coherence time, beyond the standard quantum limits, squeezed states, outperform uncorrelated systems
QS industrialization	Q-IoT, hybrid implementation with classical systems
QS technologies	trapped ions, cold atoms, transmons, Q-dots, spin-defects, REI in matrix, all photonic

R&D and industrialization of QIT should go in pair with training of professional workforce at academic and vocational levels, working on large variety of use cases, building of user

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communities, and showing high effectivity of new technologies to the public. Balanced development of regional QIT infrastructure in Europe is strongly reflected in local initiatives undertaken in Poland. These activities are either supported by the universities, government, local administration, business relations or are interconnected with European projects like the EQF, EuroHPC, etc. Several medium scale NISQ infrastructures [4,5] are just under construction for such purposes as general and quantum cybersecurity and QKD, quantum class safe links between Alice and Bob, supercomputing center enriched with quantum coprocessor, etc. A part of this effort is teaching graduated students and Ph.D. students in QIT, and awaking interest in this field among young researchers at several universities in Poland.

II. ALL OPTICAL QIT?

All optical QIT would solve a lot of current issues if only we were able to close, on the efficient technology level, the full set of necessary components.

Quantum information can be encoded more efficiently in a multi-level system than in a two-level system. The photon qubit must be transformed into the qudit form, which we not very nicely called here the qudit-ization of the photon, a multi-level quantum system. The transformation to a quantum multi-level system is not linear, it completely changes the way information is processed in the processor and in the quantum network. In classical and quantum networks we deal with multilateral relations, not only bilateral ones. In the classic network, multilateral relations are implemented, for example, by broadcasting. In the quantum world, and hence in the domain of quantum information technologies, one of the quantum no-go laws, no-broadcasting, not dissemination, strictly applies. It results from such fundamental physical laws as the limited speed of light in vacuum, the Heisenberg uncertainty principle, the impossibility of copying and deleting quantum information, etc. Quantum broadcasting must be carried out by other methods, indirectly, and in such operations quantum multi-level qudits, preferably photon qudits, may efficiently help.

In the field of quantum information technologies, including telecommunications, computing, sensors and remote sensing, clocks and attosecond timing, such terms appear in relation to the photon as photon engineering, photon quality, photon components, distinguishability and indistinguishability of photons, quantum statistics of single photons and multiphoton systems and the HOM Hong-Ou-Mandel phenomenon, dressing a photon, degrees of freedom of a composite photon, various types of two-photon systems separated and concentrated spatially, with different content of components, correlated, bilaterally and multilaterally entangled, multi-dimensionally and multi-level entangled, multiphoton systems, complex photons in time and frequency domains, etc. All the listed research areas of photon engineering are directed at the functionalization and distillation of strong, irreducible non-classical phenomena from them. Some of these non-classical entities, and potentially all of them, can be resources for functional applications. We also talk about the strength or depth of the non-classicality. It means the amount of exceeding Bell's inequality for a particular case. The greater the excess, the stronger the non-classicality.

The information resource in a quantum telecommunications network is entanglement, and generally speaking, potentially any non-classicality. Among the various classes of entanglement available, it should be magic entanglement, distillable, not simulated by classical methods, strongly quantum. It should be a multi-level, multi-dimensional entanglement modeled with qudit gates and circuits. It is also about the class of qudits that are indecomposable / not easily separable, or not decomposable at all, into qubits. The node of an effective quantum network must operate in multidimensional Hilbert space. For these and many other reasons, we would prefer to see a volatile photon qudit in a quantum network. In theory, such a qudit in the appropriate processor system will handle every operation in the quantum network.

In practice, we are far from such a possibility. We would like it to be possible to transfer full information contained in the flying qudit and the register of such qudits to the appropriate register of stationary qudits, and vice versa, in a hybrid light-electronics system. The photon qudit is formed entirely in the source and possibly in the material medium through which it is transferred. However, the interaction with the medium must be at the quantum level that manages all the characteristics of the photon, in particular all components of its near field and envelope shape. The source of photon qudit is, for example, a molecule. The source of photon qudit is not a classical laser. Qudit carries the signature of the source. The success of building quantum networks depends on the development of volatile qudits technology and mastering functional operations on them.

A network node in linear optics technology is an interesting alternative, but currently more difficult to implement than, for example, transmonic technologies due to the lack of effective functional components outside the set of logical operations, i.e. repeaters, memory, qubit/qudit type converters, etc. Such components must also appear in an integrated form that does not distort quantum information. A network node or a quantum computer in the linear optics technology in the logical part consists of non-deterministic single, double and multi-qudit gates. The qudit size is defined by the number of photon states of a single photon in the space of at least three-dimensional optical states. This size should be optimized for the application. All available quantum levels should be functionally used. Otherwise, we may not know what is happening in the available but unused quantum levels. The involved early approaches embrace the following technologies: KLM, cluster state CSQC and its implementations like linear optical LOQC, one way OWQC. Applying optical angular momentum OAM opens high dimensional Hilbert space to a single photon.

III. QUDITS – ADVANTAGE OF MULTIPLE DIMENSIONS

A. Qudit

Qudit, a d-level quantum system is an emerging alternative to better known 2-level qubits. They can be created using similar ways as qubits and offer a larger state-space for storing and processing information. A qudit can be represented as a vector in the d-dimensional Hilbert space with base $\{|i\rangle \text{ for } i = 0, \dots, d-1\}$:

$$|\alpha\rangle = \sum_{i=0}^{d-1} \alpha_i |i\rangle = \begin{pmatrix} \alpha_0 \\ \alpha_1 \\ \alpha_2 \\ \vdots\ \alpha_{d-1} \end{pmatrix} \in C^d \quad ,\text{where } \sum_{i=0}^{d-1} |\alpha_i|^2 = 1$$

Such object can replace a qubit in quantum algorithms and, because of its larger dimensionality can reduce the number of qudits required for implementation of quantum algorithms, such as travelling salesman problem [6].

B. *Quantum gates*

An universal gate set is any set of quantum gates, to which any operation can be reduced. Such set, in the domain of qubits can consist of rotation operators, phase shift gate and the CNOT gate. Such set can be formed for the qudit computation. Here such set can consist of a phase gate $Z_d(\theta)$, unitary transformations $X_d^{(l)}(x, y)$, which are created by decomposition of a transformation mapping and d-dimensional qudit to state $|d - 1\rangle$ [7]. These gates operate on a single qudit. The last required set of gates consists of controlled version of Z_d or $X_d^{(l)}$, which can be represented as

$$C_2[R_d] := \begin{pmatrix} 1_{d^2-d} & \\ & R_d \end{pmatrix} \quad ,\text{where } R_d \in \{Z_d, X_d^{(l)}\},$$

and is a two-qudit gate. Universal gate sets with smaller number of gates can be found, which is desired, since large size of the universal set implicates a more complex control system.

C. *Physical implementation*

Some quantum properties of physical systems used to implement qubits can have more than two values and thus can be used to create qudits. For example, to create a qudit with a photon, either frequency bin or time bin can be used. Additionally, generation of entangled pairs of photon qudits, which used frequency bins, has been demonstrated[8, 9]. Whereas implementation of quantum gates on photon qudits has been demonstrated, the most important use for photons would be quantum communication, as photon qudit improve the bandwidth of such links[10].

Another way to make qudits is to use the spin of a trapped ion. An ion can be trapped in an electromagnetic trap - spin of these particles combined with phonons of their vibrations make qudits. Spin of the atom can be controlled with laser pulses and phonons facilitate interactions between ions[11].

D. *Advantages*

The main advantage of a qudit system is, as previously mentioned, the larger state space represented by a single qudit compared to qubit. For this reason, a number of qudits required to represent the same state-space is smaller by a factor of $log_2 d$. Consequently this reduces the number of gates required to perform operations, such as a Toffoli gate by a factor of $(log_2 d)^2$[7].

Qudits also have advantage when it comes to quantum communications. A qudit system has higher resistance to noise compared to a qubit system, since noise influences every qudit/qubit individually and the qudit system requires less qudits compared to a qubit system[7, 10]. Improvement of the noise resilience improves robustness of the communication system, which is a desired effect.

E. *Challenges*

The main challenge of qudit system is the more complex control it requires to implement quantum gates[12]. Especially using photons requires very precise measurement systems, to correctly measure parameters of such qudits[9, 10].

F. *Conclusion*

Currently not many real-world implementations of the qudit processors or communications exist and most of them are experimental setups. However, clear advantages such systems provide, it should be reasonable to assume these system would become more widely available.

One of companies aiming to introduce a quantum computing system using qudits is Quantum Computing Inc. with their Dirac-2. Whereas there isn't much information published on how it is implemented, it seems to be a photonic system using time bins.

IV. CYBERSECURITY IN THE QUANTUM ERA

Current cryptography techniques used for cybersecurity could face a serious threat from quantum computers. This is due to the fact that quantum computers are capable of solving complex mathematical issues that are either challenging or very time-consuming for traditional computers. One such problem is integer factorization, which is used in many encryption algorithms. Widely used RSA encryption algorithm relies on the difficulty of factoring large integers to protect data. However, a sufficiently powerful quantum computer could factor large numbers efficiently and break RSA encryption. Similarly, the widely used elliptic curve cryptography (ECC) is also vulnerable to attacks by quantum computers. Also fast solving the discrete logarithm is not a problem for quantum computer. It is a thread to fintech sector (payment systems, e-banking) and Blockchain-based solutions.

New cryptography methods that can withstand quantum computing are being created to prevent this hazard. The mathematical issues used in these methods are thought to be challenging even for quantum computers to solve. Examples of this are hash-based cryptography lattice-based cryptography and code-based cryptography. To counter the threat posed by quantum computers, new types of security systems are also being developed. Technique for safely distributing encryption keys that is resistant to attacks by quantum computers is Quantum Key Distribution (QKD).

Quantum key distribution is a secure communication technique that distributes secret keys between two parties utilizing the ideas of quantum physics. Example of the start of communication [14]:

1. Key Generation: The sender (Alice) must first create a random string of 1s and 0s that will serve as the secret key. The recipient (Bob) is then informed of this key by Alice using photons, which are light-related particles.
2. Quantum transmission: Using a communication medium, such as a fiber optic cable or the air, Alice transmits the photons to Bob. Each photon, which represents a piece of the secret key, is sent one at a time.

3. Detecting: Bob gets the photons and uses a detector to measure them. The act of measuring the photons, however, modifies them according to the laws of quantum physics, making obvious any attempt to eavesdrop on the transmission.

4. Validation: To ensure that the key is identical on both sides, Alice and Bob compare a section of the key. The key is deemed secure and can be used for encryption if there is a match. If the compared bits of Alice and Bob are different, it means that the message was overheard or there was a disturbance during transmission. The key should be rejected.

5. Further Communication: Once the key has been established, Alice and Bob can use it to safely send messages via an communication channel. Messages can be encrypting and decrypting by safe key.

The biggest advantage of Quantum Key Distribution is unconditional security that is guaranteed by principles of quantum mechanics. It is impossible to measure a quantum system without changing it. This solution seems to be also future-proof. Attacker cannot use more advanced technology to break the encryption. That technology is also efficient in terms of the amount of data that can be transmitted securely. So, QKD is appropriate for a wide range of applications since it can safely transmit massive amounts of data.

The problems that currently exist with Quantum Key Distribution are related to the early stage of development. Limited range because quantum states is sensitive to losses and noise in the communication channel [13]. The system complexity is high, that makes costs and requires specialists.

Despite these difficulties China lunched in 2017 impressive QKD network. It connects Shanghai with Beijing, spanning more than 2000 km[15] and it is growing all the time. China also participated in a project to establish a quantum-secure intercontinental link by making secured video call with Vienna, Austria. Distance between connected points was approximately 7,500 km long. Other countries with huge success in quantum distribution key are USA (DARPA Quantum Network), Canada (quantum connection with moving aircraft), Swiss and India. The European Union does not want to be left behind so it launched the Open European Quantum Key Distribution Testbed program that will connect 10 countries by a quantum secured connection.

Another aspect related to cyber security are random number generators. Really random numbers are necessary for many cryptographic applications, including key creation and authentication, and can be produced by quantum computers. Quantum physics' inherent unpredictability allows for the generation of totally unpredictable and unrepeatable numbers. Such generators are currently in use. An example of the use of a quantum random number generator is the generation of key bits in QKD. In the previously presented example of using a quantum key, the use of this technology occurs at point 1. Key Generation.

As you can see, quantum cyber security is not just a concept. Working systems are in use around the world. Perhaps in the near future their use will increase to the point where a banking transaction or blockchain solutions will be based on cyber-quantum security.

V. QUANTUM ALGORITHMS – A BRIEF OVERVIEW AND POTENTIAL USES

A. Quantum Turing Machine

To get a better understanding of how quantum algorithms work it is important to familiarize oneself with the concept of Quantum Turing Machine (QTM). The model proposed by David Deutsch in 1985 is a generalization of classical Turing Machine (TM) with the main difference being that the operations for the set of states Q are represented by unitary transformations confined to two-dimensional Hilbert Space. That representation is necessary because quantum computations are being performed in parallel as a result of a quantum state collapsing into a single superposition [16]. For example, a set of m qubits containing 2^m possible quantum states is able to compute the corresponding 2^m values of a quantum function simultaneously using just one unitary operation as opposed to checking the function values 2^m times.

B. Chosen popular quantum algorithms

Certain quantum algorithms, that are often described in academic literature, may not always have practical use; however, their simplicity can be used to explain the nature of quantum computing in greater detail. An example of such an algorithm is the Deutsch-Jozsa algorithm [17].

The Deutsch-Jozsa algorithm is a kind of quantum oracle that checks whether a binary function $f(x)\colon \{0,1\}^n \to \{0,1\}$ is either constant or balanced. If the function is balanced, then exactly half of output values is equal to 0 and the other half is equal to 1. The classical approach solving this problem would require 2^n checks of the function to provide oracle's answer. The quantum approach on the other hand requires only one check of the binary function due to quantum parallelism.

Similarly, the algorithm solving the Simon's problem [17] takes the aforementioned binary function $f(x)\colon \{0,1\}^n \to \{0,1\}$ and looks for its period. The decrease of computational complexity from approximately $\Omega\left(\sqrt{2^n}\right)$ in the classical brute-force approach to $O(n)$ is achieved by utilising both quantum parallelism and quantum entanglement. The latter allows for finding output vectors separated by initial function's period.

Amongst more popular quantum algorithms, some have proven to have possible practical applications such as Quantum Fourier Transform (QFT). Discrete Fourier Transform (DFT) is a unitary operation [17] therefore its definition $F_y(f) = \frac{1}{\sqrt{N}}\sum_{x=0}^{N-1} f(x) e^{\frac{2\pi jxy}{N}}$ can be applied to the vector of n-qubit quantum states amplitudes. The main improvement of QFT over DFT is reduced memory complexity from $O(n \cdot 2^n)$ gates to $O(n \cdot \log n)$ Hadamard gates. The QFT algorithm has already found its use in the development of other quantum algorithms such as Shor's algorithm [17].

C. Noteworthy examples of quantum algorithms

New quantum algorithms are being continuously developed and published [18] with some showing promise. For instance, the algorithm designed by Harrow, Hassimid and Lloyd to solve linear equations (HHL) [19] outputs the solution vector x such that $Ax = b$ as an N-dimensional quantum state. If the input matrix A satisfies certain constraints including sparsity and having condition k , then the computational complexity of HHL algorithm is $poly(\log N, k)$ as opposed to polynomial complexity of methods such as Gaussian elimination.

Similarly to HHL algorithm, a method proposed by Guoming Wang [18][20] provides an efficient way to analyze large electrical networks. In the aforementioned method an electrical network is modeled as a weighted graph of n vertices and d being the maximum unweighted degree of the vertices. Edge weights of the graph are interpreted as electrical resistances in the network. Two algorithms proposed in the method run in $poly\left(\log n, d, \frac{1}{\phi}, \frac{1}{\epsilon}\right)$ time, where ϕ is the normalised Laplacian of the network and ϵ is the accuracy of the algorithm.

D. Halting problem of Quantum Turing Machine

In spite of computational complexity improvements provided by the quantum nature of computing over classical methods, QTM is a superset of classical TM and cannot solve the Halting problem as proven by Takayuki Miyadera and Masanori Ohya in 2004 [21]. To be precise, a universal solution to the Halting problem that is independent of QTM theoretical model is proven to not exist. The result of the proof suggests that quantum algorithmic complexity theory may need to be constructed.

VI. QUANTUM STEERING INTO THE PAST

Quantum effects such as superposition or entanglement are well known to most people because they have been popularized by popular science content. These phenomena are well researched and being used in quantum information technologies. However, there are exciting quantum effects that are still under research and their applications might bring groundbreaking technologies. One of these effects is quantum steering into the past.

This property was proposed by John Wheeler in a series of his thought delayed-choice experiments. It can be explained with Mach-Zehnder interferometer consisting of two mirrors and two beam-splitters where second beam-splitter is removed on random basis[25]. If the second beam splitter is present photons demonstrate wave properties, where on the first beam-splitter half of the energy goes through the beam-splitter and half is reflected and on the second beam- splitter those waves are combined resulting in interference pattern.

However, if the second beam-splitter is removed, photons show particle properties, where on the first beam-splitter photon chooses to go either through or reflect from the first beam-splitter and is detected only on one of the detectors. Quantum steering into the past appears if we decide whether to keep or remove the second beam-splitter when the photon is already in the system. If the presence of the beam-splitter is what determines properties chosen by the photon, then the choice of removing the beam-splitter that is happening in the future would have to influence photon's choice which happened in the past.

This seems as another hard to comprehend quantum phenomenon but can actually be explained by superposition and photon always being represented by the wave function until the measurement, when its wave function collapses to a single point. After passing the first beam-splitter photon goes into superposition of 50% passing through the beam-splitter and 50% reflecting from it. Then it will interfere with itself if the second beam-splitter is present or not if it is removed and its superposition will collapse on the screen where we will observe interference pattern or not.

There is, however, an experiment performed by Ma et al. where there is no simple explanation for actions in the future influencing the past. They performed a delayed-choice entanglement swapping experiment. In classic entanglement swapping two pairs of entangled photons are produced, 1&2 and 3&4. Photon 1 is given to Alice, photon 4 is given to Bob and photons 2 and 3 are given to Victor. Then Victor entangles his two photons resulting in the entanglement of photon 1 and 4. Alice and Bob can measure their photons and when they compare their results, they find out their photons have been entangled even though they never interacted with each other. To observe quantum steering into the past we have to change the timing of the events. In t_1 two pairs of photons are generated, in t_2 Alice and Bob perform their measurement, in t_3 decision whether Victor entangles his photons is made and in t_4 Victors entangles his photons or not. Ma in his experiment uses 104m fiber to ensure that $t_1 < t_2 < t_3 < t_4$.

To further make sure that photons have no way of knowing Victor's decision, quantum random number generator is used to decide whether to entangle photons. This experiment proved that even though Victor's decision was made posteriori to the measurement of photons 1 and 4 it influenced its results.

If one views the quantum state as a real physical object, one could get the seemingly paradoxical situation that future actions appear as having an influence on past and already irrevocably recorded events. However, if the quantum state is viewed as "catalogue of our knowledge", then the state is a probability list for all possible measurement outcomes, the relative temporal order of the three observer's events is irrelevant and no physical interactions whatsoever between these events, especially into the past, are necessary to explain the delayed-choice entanglement swapping[24].

When mastered quantum steering into the past can allow access to whole new chapter of quantum information technologies. However, it was only achieved in laboratories and has several difficulties to overcome before we will see the first technologies using this phenomenon.

VII. OPTICAL QUANTUM SENSORS

Optical solutions in quantum technology are widely used as a consequence of highly favorable nature of photons as a quantum medium. Their natural coherence, many ways of encoding and low interaction with their surroundings, affirms them both as a main means of information transfer in quantum communication or measurement, and as a possible candidate for future quantum computers.

Light in optical quantum solutions can be encoded in a number of ways - quantum optical sensors operate mainly based on changes in frequency, dispersion, and orbital angular momentum. In case of multiple photons - also by interferometry or with addition of entanglement - in energy, momentum, and polarization degree.

Beyond strictly optical detectors, there also exists a wide field of plasmonic sensors utilizing surface plasmons to which light is coupled through other optical means such as microcavities or resonant processes.

With use of squeezed and entangled states of light, it is possible to surpass the standard quantum limit and achieve resolutions closer to the Heisenberg uncertainty. The first of those utilizes (generally by means of parametric down conversion) relinquishing of the accuracy in either phase or amplitude, allowing to lower the uncertainty of the corresponding physical quantity below the vacuum fluctuation level. The latter characterizes states consisting of multiple photons, where each photon can't be described independently from others.

Difficulties pertaining to the operation of an optical sensor and its effective sensitivity can be differentiated by the main components of any sensor. In their case - the photon emitters and detectors. The medium acting as a bridge between the two also comes with its own issues - for example, such as losses typical for the material used in case of integrated photonics which thus limit spectral range of the sensor[23].

Presently main technologies in single emitter solutions of quantum optical sensors include generators based on quantum dots, nitrogen vacancy centers, hexagonal boron nitride defects, quantum frequency combs, and nonlinear sources and resonators. Depending on their target application, it is possible to choose a dedicated solution among them, as they differ as to their main advantages - such as biocompatibility, operation in room temperature, high information density or correlation of originating photons. Each of them also presents a compromise between their advantages and possible difficulties, which must be compensated by other means[22].

As for photon detection, it is mainly accomplished by use of avalanche photodiodes and, in lower temperatures, by superconducting nanowires, single-photon detectors, transition-edge sensors and visible light photon counters. Main difficulty concerns the compromise between higher resolution and operation in lower temperatures - which brings the possibility of thermal noise occurring on connectors to the rest of the system[23].

Already there have been quantum optical sensors assembled in laboratory conditions in integrated photonic systems. Main reservations are the ones common also to the optical systems of linear optics quantum computing - the difficulty of providing reliable single photon emitters and detectors in room temperature, with lossy waveguides. Inevitable noise constitutes the main holdback from achieving more reliable results with higher resolution.

Despite other quantum sensor technologies, the optical sensors offer a wide variety of solutions, whose shortcomings are progressively overcome by abundant continuous research, not necessarily in the area of quantum computing, but in purview of such fields as integrated photonics or material engineering. Although with still present noise difficulties, optical sensors offer multiple solutions at room temperature which may be in future used in photonic integrated systems, rendering them as feasible mass-distributed quantum sensors and not used, as of now, solely in dedicated applications.

VIII. DISCUSSION, CONCLUSIONS

The network node is a quantum computer, generally implemented in any technology, e.g. transmon, ion, quantum dots, color centers, but also photonic integrated in the PIC quantum format, referred to as IQPP (integrated quantum photonic processor). If we isolate the generation of the simplest two-photon spatial qudit, where we use non-linear phenomena such as SPDC/FWM and single-photon quantum detectors PNRD (photon number resolving detectors), then all the rest of the logical operations can be performed in a linear integrated optical system composed of integrated classical optical elements such as a lens, diffraction grating, and in particular multiple 50/50 splitters of single photons qubits/qudits.

The advantage of the IQPP technology is the extraordinary simplicity of linear optical operations and the weak coupling of the photon qubit/qudit with the thermodynamic environment. This means that the IQPP processor can operate at room temperature, i.e. unlike most other quantum processor technologies. Despite the many advantages of the IQPP processor that supports the network node and the advantages of optical fibers optimized for the transmission of photon qudits and reaching such a node, we are still, and will remain for quite a long time, at the stage of small-scale systems. The scalability is related to the currently limited speed of quantum error correction and the lack of ability to operate effectively in the area of qudit hyper-entanglement. In addition to the discussed methods and topological OAM domains of photon qudit generation and existence, significant progress is observed in the functionalization of the frequency domain, quantum frequency comb and, in the future, the potential synthesis of any photon qudit.

Several fields of the QIT with a potential for a rapid development in near future are discussed. Most recognizable and rapidly improving quantum processors show promise of implementation of various quantum algorithms and test them on sufficient scale to further develop them.

Quantum processors have an ability to solve some classes of problems much more efficiently compared to classical computers, which will pose a threat to some encryption mechanisms in the future. For this reason quantum-proof alternatives, like QKD, are developed.

This however, is only one of the many technologies being developed. Using qudits instead of qubits have potential to vastly improve performance of quantum systems and quantum processors. Especially photonic implementations of qudits (IQPP – integrated quantum photonic processor) may be used in quantum communication systems. For this reason a variety of optical quantum sensors are developed. Precise measurement of photon properties, like frequency or angular momentum is necessary for quantum applications.

Some less known quantum phenomena are also researched and their applications are developed, such as quantum steering into the past, which might have fascinating implications for quantum communication and encryption.

These fields show real potential for improvement of quantum communication and computing. Better quantum processors and sensors should improve our understanding of the quantum world. This can have a profound impact on other disciplines, such as chemistry and medicine.

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