IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received August 24, 2021, accepted September 26, 2021, date of publication October 13, 2021, date of current version November 16, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3119588

A Novel Efficient Quantum Random Access Memory

MOHAMMED ZIDAN[1], ABDEL-HALEEM ABDEL-ATY[2,3], ASHRAF KHALIL[4], MAHMOUD ABDEL-ATY[5], AND HICHEM ELEUCH[6,7]

[1]Department of Artificial Intelligence, Faculty of Computers and Artificial Intelligence, Hurghada Branch, South Valley University, Egypt
[2]Department of Physics, College of Sciences, University of Bisha, Bisha 61922, Saudi Arabia
[3]Physics Department, Faculty of Science, Al-Azhar University, Assiut 71524, Egypt
[4]College of Technological Innovation, Zayed University, Abu Dhabi, United Arab Emirates
[5]Department of Mathematics, Faculty of Science, Sohag University, Sohag 82524, Egypt
[6]Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates
[7]Department of Applied Sciences and Mathematics, College of Arts and Sciences, Abu Dhabi University, Abu Dhabi, United Arab Emirates

Corresponding author: Mohammed Zidan (comsi2014@gmail.com)

ABSTRACT Owing to the significant progress in manufacturing desktop quantum computers, the quest to achieve efficient quantum random access memory (QRAM) became inevitable. In this paper, we propose a novel efficient random access memory for quantum computers. The proposed QRAM has a fixed structure and can be used efficiently to store both known and unknown classical/quantum data. The storage capacity of the proposed QRAM is more efficient than that of the classical RAMs and can be used to store both classical and quantum information. Furthermore, the proposed model can access an arbitrary location in $O(1)$ compared with other state-of-the-art models.

INDEX TERMS Quantum random access memory, quantum circuits, quantum algorithm, quantum computers.

I. INTRODUCTION

The unique properties of quantum mechanics, i.e. superposition and entanglement, have revolutionized the speed of quantum computing. Quantum teleportation is a novel technology that can be used for transferring unknown quantum states [1], [2]. Previous research has shown that quantum computers solve complex computing problems faster than classical computers [3]–[8]. Recently, it has been proved that quantum computers can solve novel types of problems that are impossible to solve using classical computers [9]. Thus, the quest to achieve efficient quantum random access memory became inevitable. Also, the power of computing devices is based on the capacity to store information in an array of memory cells. Random access memory (RAM) is classified as an architecture for a memory array [3]. RAM has three ingredient components: an array of memory cells, an address register and an output register. Each cell is addressed with a unique address from 2^n addresses. When the address register is loaded with an address, the corresponding cell content is retrieved via the output register.

RAM is the primary memory in classical computers. Quantum primary memory, QRAM, is the main infrastructure to build a powerful quantum computer. Quantum computer applications and quantum control systems require creating variables in QRAM. Each variable name is translated to a reserved address that points to a unique location, containing the variable value, in the QRAM. In this paper, we propose a novel QRAM model for storing classical data and quantum data in 2^n different states inside QRAM. The quest of implementing QRAM is essential for the implementation of quantum algorithms [3]–[8]. Moreover, QRAM would provide an exponential speed up for pattern recognition algorithms [5], [10]–[15]. In [16], Giovanetti *et al.* proposed addressing a QRAM architecture called the "bucket brigade" [16] that needs $O(n)$ to call a memory cell. The nodes of the routing binary tree are represented by three level quantum systems (qutrits) [16]. To study the efficiency of the bucket brigade scheme, Arunachalam *et al.* [17] showed the circuit model for the quantum bucket brigade architecture and investigated the quantum error correction for the circuit. This QRAM [16] needs a qutrit-based system to be implemented, i.e. it cannot be implemented on qubit-based quantum computers. Recently, Park *et al.* [18] proposed Flip-Flop

The associate editor coordinating the review of this manuscript and approving it for publication was Wei Huang.

Quantum Random Access Memory (FF-QRAM) based on the quantum circuit model. A main component of a FF-QRAM circuit is the controlled qubit rotation $C^nR_y(\theta^l)$ that must be used to store data item l [18]. This means that the structure of this QRAM [18] is data dependent. In this paper, we propose a novel efficient quantum random access memory for quantum computers. Unlike FF-QRAM [18], the proposed QRAM has a fixed structure. Also, unlike bucket brigade QRAM [16], the proposed QRAM can be implemented on qubit-based quantum computers. Moreover, the proposed QRAM can be used to efficiently write both known and unknown classical/quantum data. The storage capacity of the proposed QRAM is high compared to that of classical RAM. Furthermore, the proposed model can access arbitrary location in $O(1)$ compared with other state-of-the-art models.

The remainder of this paper is organized as follows. In section 2, we present the proposed QRAM model and the proposed reading and writing algorithm. In section 3, we analyze performance of the new QRAM. Section 4 illustrates the experimental results of the simulation of the proposed QRAM. Finally, section 5 concludes the paper by accentuating its main findings.

II. THE PROPOSED QUANTUM RANDOM ACCESS MEMORY (QRAM) CIRCUIT

A. THE PROPOSED QRAM CIRCUIT

Fig.1 shows the circuit of the proposed Quantum Random Access Memory (QRAM). The register $|A\rangle$ represents the address register used to address the locations of the register $|D\rangle$, so the register $|A\rangle$ determines the locations of the variables in QRAM. The size of the register $|A\rangle$ is n qubits to address $2n$ locations in the QRAM. Consequently, the size of $|D\rangle$ is m qubits, which is addressed by 2^n locations in the QRAM. Moreover, an extra qubit $|dq\rangle$ is initialized at state $|0\rangle$. $|qy\rangle$ is a $n + m$ qubit-sized bus register, which links the quantum processor/micro-controller and QRAM. The first n qubits of the bus register $|qy\rangle$ are used to carry the address of the variable location provided by a quantum computer or a quantum microcontroller while the other m qubits are used to carry the value in the variable to transfer it to a specific location in the quantum RAM or are used to read the data from QRAM. Finally, an extra qubit $|r\rangle$ is used to distinguish between reading and writing processes. In this model, the correlation between the memory cell and its address occurs via entanglement when the writing process is performed. This QRAM model has the potential to store classical data or a superposition of states into a single location. Hence, the capacity of the proposed model increases exponentially compared to that of classical RAM.

B. THE NEW QRAM READING AND WRITING ALGORITHM

In this section, we present the algorithm that handles reading and writing operations for the proposed QRAM model.

1) Register Preparation: $|\psi_0\rangle = H^{\otimes n}|A\rangle^{\otimes n} \otimes I^{\otimes n}|D\rangle^{\otimes n} \otimes I|dq\rangle \otimes I^{\otimes 2n}|qy\rangle^{2n} \otimes I|r\rangle$, such that each register is initialized by the vacuum state $|000\ldots0\rangle$.
2) $|\psi_1\rangle = \prod_{i=1}^{n} NOT_{A_i} C^{not}_{qy_iA_i}|\psi_0\rangle$.
3) $|\psi_2\rangle = T^n_{A_1A_2\ldots A_ndq}|\psi_1\rangle$.
4) $|\psi_3\rangle = \prod_{i=1}^{m} T^3_{r\,dq\,D_i\,qy_{n+i}} C^0 - C - SWAP_{r\,dq\,qy_{n+i}\ D_i}|\psi_2\rangle$.
5) $|\psi_4\rangle = T^n_{A_1A_2\ldots A_ndq}|\psi_3\rangle$.
6) $|\psi_5\rangle = \prod_{i=1}^{n} NOT_{A_i} C^{not}_{qy_iA_i}|\psi_4\rangle$.

III. PERFORMANCE ANALYSIS OF THE NEW QRAM

1) Step1: The algorithm applies n Hadamard gates. Each of them is applied to a single qubit of the register $|A\rangle$ to create a complete superposition of states in the register $|A\rangle$ to address 2^n locations in the QRAM.
2) Step 2: When an address is loaded in the first n qubits of the bus register $|qy\rangle$, the QRAM needs to find the address location among 2^n addresses of the register $|A\rangle$, which is assigned by a quantum processor via the bus register $|qy\rangle$. To find this location, a set of n $CNOT$ gates are applied between each qubit of the bus register $|qy\rangle$ as a control qubit and the corresponding qubit in the register $|A\rangle$ as a target qubit. Then, a set of n quantum-NOT gates are applied to the qubits of the register $|A\rangle$ individually. The result of this operation transforms the required location in the register $|A\rangle$ to be in the state $|11\ldots1\rangle$ in the superposition.
3) Step 3: The Toffoli gate is used to mark the address that matches the input address in the bus register $|qy\rangle$ by entangling $|dq\rangle$ with the QRAM. The Toffoli gate is defined as

$$T^n_{A_1A_2\ldots A_ndq} = |A_1A_2\ldots A_ndq, (A_1A_2\ldots A_n + dq) mod 2\rangle.$$

4) Step 4: The QRAM performs a reading or writing process from a given location provided by the quantum processor through the first nth qubits of register $|qy\rangle$ based on the state of the qubit $|r\rangle$ as follows:

(i) If the qubit $|r\rangle$ is loaded with state $|1\rangle$ by the quantum processor, then the $T^3_{r\ dq\ D_i\ qy_{n+i}}$ is run to copy the value of the variable to the last m qubits of the register $|qy\rangle$. Furthermore, the $C^0 - C - SWAP_{r\ dq\ qy_{n+i}\ D_i}$ is not working, so the reading process is complete.

(ii) However, if the quantum processor loads the state $|0\rangle$ to the qubit $|r\rangle$, then the controlled-controlled-swap, $C^0 - C - SWAP_{r\ dq\ qy_{n+i}\ D_i}$, gate is applied to write the value stored in the last n qubits of the register $|qy\rangle$ into the QRAM location specified by the first n^{th} qubits. Furthermore, the $T^3_{r\ dq\ D_i\ qy_{n+i}}$ gate is not working, so the writing process is complete, $C^0 - C - SWAP_{r\ dq\ qy_{n+i}\ D_i}$ is the swap gate controlled by the qubit $|r\rangle = 0$, and the qubit $|dq\rangle = 1$.

5) Step 5: Remove the entanglement between qubit $|dq\rangle$ and register $|A\rangle$ by applying the Toffoli gate to disentangle it.
6) Step 6: Remove the effect of the first step by applying a set of n $CNOT$ gates between each qubit of the bus register $|qy\rangle$ as a control qubit and the corresponding

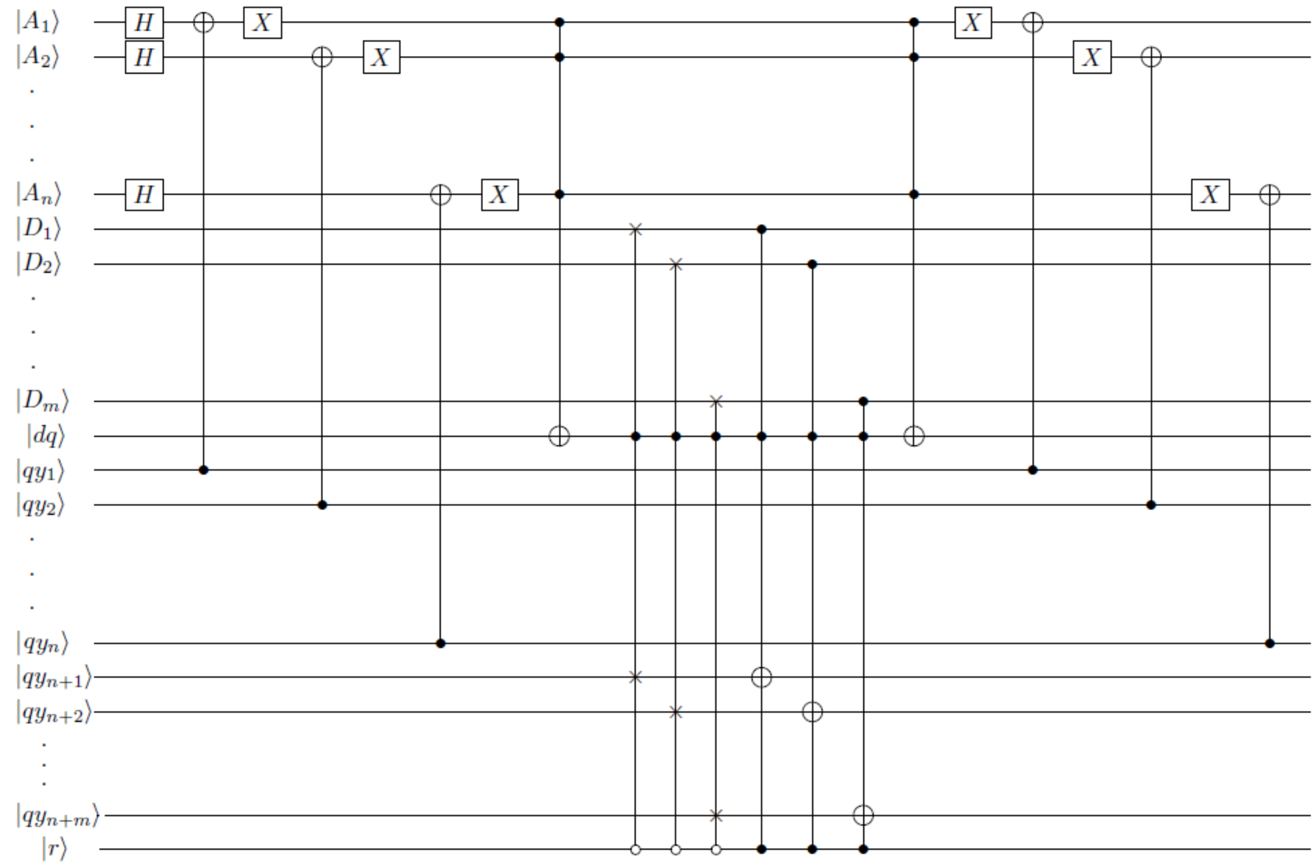

FIGURE 1. A quantum circuit for the proposed quantum random access memory (QRAM).

qubit in the register $|A\rangle$ as a target qubit. Then, a set of n quantum-NOT gates are applied on the qubits of register $|A\rangle$ individually.

IV. EXPERIMENTAL REALIZATION OF THE PROPOSED QRAM

To verify the QRAM practically, we will conduct some experiments for writing and reading classical values in the proposed QRAM using the Javantum simulator. First, to simulate the writing process of the proposed QRAM, let us assume that there is an application that performs some tasks using four variables x, y, u, and z. Also, let us assume that this application requires assigning the value 7 (111 in binary) to variable x (that has the address 00). As the number of variables is four, then 2 qubits are needed to address register $|A\rangle$. The simulation results of writing the binary value 111 in the address label 00 are shown in Fig. 3. In this bar chart, the green bars represent the theoretical results, and the red bars represent the Javantum simulator results. Fig. 3 shows that the simulation results are consistent with the theoretical results.

Second, to simulate the reading process of the proposed QRAM, we need to read the value of variable x (that has the address "00") that was written as 111. The simulation results of reading the binary value 111 from address label "00" are shown in Fig. 4. This figure shows that the simulation results match the theoretical results. Next, we will conduct some experiments for writing and reading quantum states in the proposed QRAM using the Javantum simulator. Third, suppose that it is essential to save state $\sqrt{\frac{1}{2}}|00\rangle + \sqrt{\frac{1}{2}}|11\rangle$ in address label "00". The simulation results of writing state

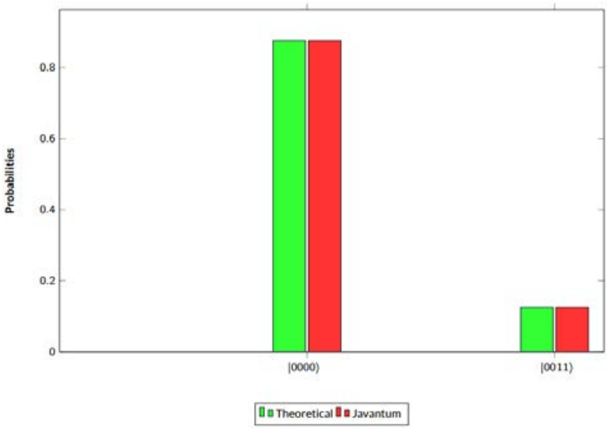

FIGURE 2. Simulation results of reading the quantum state $\sqrt{\frac{1}{2}}|00\rangle + \sqrt{\frac{1}{2}}|11\rangle$ from address 00.

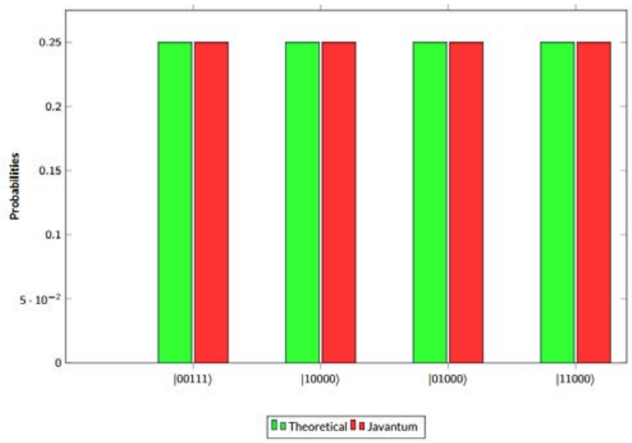

FIGURE 3. Simulation results of writing the value 111 into address 00.

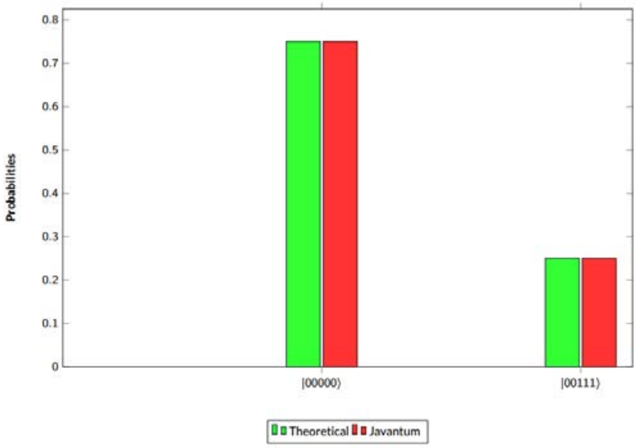

FIGURE 4. Simulation results of reading the value 111 from address 00.

$\sqrt{\frac{1}{2}}|00\rangle + \sqrt{\frac{1}{2}}|11\rangle$ in address label "00" are shown in Fig. 5. In this bar chart, the green histograms represent the theoretical results, and the red histograms represent the Javantum simulator results. Fig. 5 illustrates that the simulation results match the theoretical results. In the final experiment, it is necessary to read the superposition state, $\sqrt{\frac{1}{2}}|00\rangle + \sqrt{\frac{1}{2}}|11\rangle$, from address label "00". The simulation results of reading the superposition from address label "00" are given in Fig. 2. The figure shows that the simulations results match the theoretical results. Additionally, the statistical fidelity of the simulation results via the Javantum simulator for writing operation is 0.999971, verify the consistency with the theoretical results (since the optimal fidelity is $F = 1$). Consequently, the results of the four mentioned experiments demonstrate that the proposed QRAM is efficient as a primary memory for quantum computers and can be implemented via different quantum computer platforms. The abovementioned experiments indicate that the proposed QRAM is more efficient than FF-QRAM [18] because it has a fixed structure; uses well-known quantum gates, namely, NOT, CNOT, Toffoli and controlled-controlled-swap gates; and is data independent.

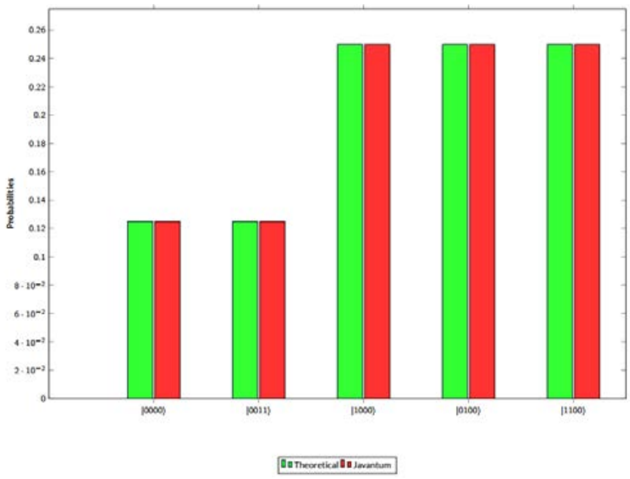

FIGURE 5. Simulation results of writing the quantum state $\sqrt{\frac{1}{2}}|00\rangle + \sqrt{\frac{1}{2}}|11\rangle$ into address 00.

In addition, the proposed QRAM does not need qutrit, so it is more efficient to implement via different quantum computer platforms compared with bucket brigade QRAM [16]. Moreover, the complexity of the proposed QRAM calls is $O(1)$ compared with bucket brigade QRAM [16] and FF-QRAM [18], which have $O(n)$ calls and $O(Mn)$ calls, respectively. Hence, the proposed QRAM is faster than other state-of-the-art models. As a result, the superiority of the proposed QRAM is remarkable compared to the existing QRAMs [16], [18].

V. CONCLUSION

In this paper, we proposed a novel QRAM circuit with a fixed structure that can be used to handle reading and writing processes and access arbitrary locations among 2^n locations in $O(1)$. Additionally, it can write data independently and can be used to store both known/unknown classical/quantum data. Moreover, it is proposed based on well-known quantum gates, such as NOT, CNOT, Toffoli, and controlled-controlled-swap gates. In addition, it can be applied to a variety of quantum qubit-based platforms. Finally, the new QRAM is simulated in a quantum computer simulator with a statistical fidelity of 0.999971.

REFERENCES

[1] J.-G. Ren *et al.*, "Ground-to-satellite quantum teleportation," *Nature*, vol. 549, pp. 70–73, Sep. 2017.
[2] C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres, and W. K. Wootters, "Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels," *Phys. Rev. Lett.*, vol. 70, no. 13, pp. 1895–1899, Mar. 1993.
[3] A. Robert, P. K. Barkoutsos, S. Woerner, and I. Tavernelli, "Resource-efficient quantum algorithm for protein folding," *NPJ Quantum Inf.*, vol. 7, no. 1, pp. 1–5, Dec. 2021.
[4] L. Huang, H. Zhou, K. Feng, and C. Xie, "Quantum random number cloud platform," *NPJ Quantum Inf.*, vol. 7, no. 1, pp. 1–7, Dec. 2021.
[5] M. Zidan, A.-H. Abdel-Aty, M. El-shafei, M. Feraig, Y. Al-Sbou, H. Eleuch, and M. Abdel-Aty, "Quantum classification algorithm based on competitive learning neural network and entanglement measure," *Appl. Sci.*, vol. 9, no. 7, p. 1277, Mar. 2019.

[6] W. Liu, Q. Wu, J. Shen, J. Zhao, M. Zidan, and L. Tong, ‘‘An optimized quantum minimum searching algorithm with sure-success probability and its experiment simulation with Cirq,’’ *J. Ambient Intell. Hum. Comput.*, vol. 12, pp. 1–10, Jan. 2021.

[7] A. Montanaro, ‘‘Quantum algorithms: An overview,’’ *NPJ Quantum Inf.*, vol. 2, no. 1, pp. 1–8, Nov. 2016.

[8] P. W. Shor, ‘‘Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer,’’ in *Proc. 35th Annu. Symp. Found. Comput. Sci.*, Santa Fe, NM, USA, Nov. 1994, pp. 124–134.

[9] M. Zidan, H. Eleuch, and M. Abdel-Aty, ‘‘Non-classical computing problems: Toward novel type of quantum computing problems,’’ *Results Phys.*, vol. 21, Feb. 2021, Art. no. 103536.

[10] H. Y. Huang, M. Broughton, and M. Mohseni, ‘‘Power of data in quantum machine learning,’’ *Nature Commun.*, vol. 12, pp. 1–9, May 2021.

[11] D.-L. Deng, ‘‘Machine learning detection of bell nonlocality in quantum many-body systems,’’ *Phys. Rev. Lett.*, vol. 120, no. 24, Jun. 2018, Art. no. 240402.

[12] K. Beer, D. Bondarenko, T. Farrelly, T. J. Osborne, R. Salzmann, D. Scheiermann, and R. Wolf, ‘‘Training deep quantum neural networks,’’ *Nature Commun.*, vol. 11, no. 1, pp. 1–6, Dec. 2020.

[13] V. Nguyen, S. B. Orbell, D. T. Lennon, H. Moon, F. Vigneau, L. C. Camenzind, L. Yu, D. M. Zumbühl, G. A. D. Briggs, M. A. Osborne, D. Sejdinovic, and N. Ares, ‘‘Deep reinforcement learning for efficient measurement of quantum devices,’’ *npj Quantum Inf.*, vol. 7, no. 1, pp. 1–9, Dec. 2021.

[14] P. Palittapongarnpim, P. Wittek, E. Zahedinejad, S. Vedaie, and B. C. Sanders, ‘‘Learning in quantum control: high-dimensional global optimization for noisy quantum dynamics,’’ *Neurocomputing*, vol. 268, pp. 116–126, Dec. 2017.

[15] A. Barr, W. Gispen, and A. Lamacraft, ‘‘Quantum ground states from reinforcement learning,’’ *Proc. Mach. Learn Res*, vol. 107, pp. 635–653, Aug. 2020.

[16] V. Giovannetti, S. Lloyd, and L. Maccone, ‘‘Quantum random access memory,’’ *Phys. Rev. Lett.*, vol. 100, no. 16, Apr. 2008, Art. no. 160501.

[17] S. Arunachalam, V. Gheorghiu, T. Jochym-O’Connor, M. Mosca, and P. V. Srinivasan, ‘‘On the robustness of bucket brigade quantum RAM,’’ *New J. Phys.*, vol. 17, no. 12, Dec. 2015, Art. no. 123010.

[18] D. K. Park, F. Petruccione, and J.-K.-K. Rhee, ‘‘Circuit-based quantum random access memory for classical data,’’ *Sci. Rep.*, vol. 9, no. 1, pp. 1–8, Dec. 2019.

MOHAMMED ZIDAN is currently an Assistant Professor with Hurghada Faculty of Computers and Artificial Intelligence, South Valley University, Egypt. Before that, he worked at the Faculty of Engineering, King Salman International University, Egypt. He also worked at the Zewail University of Science and Technology, from 2016 to 2020. In 2020, he joined the Photonic and Smart Materials Center at Zewail City, as a Postdoctoral Researcher. He holds U.S. patents in quantum computing. He has published many high impact articles in international peer-reviewed journals. His research interests include quantum computing, quantum artificial intelligence, robots, and quantum technologies. He is a member of the Egyptian Mathematical Society and a reviewer of several international journals in quantum computing and applied mathematics.

ABDEL-HALEEM ABDEL-ATY received the B.Sc. and M.Sc. degrees in physics from the Department of Physics, Al-Azhar University, Egypt, in 2004 and 2009, respectively, and the Ph.D. degree in theoretical physics (quantum information) from Universiti Teknologi PETRONAS, Malaysia, in 2015. His Ph.D. study was supported by a scholarship from Universiti Teknologi PETRONAS. He has authored or coauthored more than 120 articles in ISI journals, four book chapters, and ten papers in conference proceedings indexed by Scopus and ISI. He is especially focused on theories of quantum measurement, nanomechanical modeling, highly nonclassical light, practical information security, and the optical implementations of quantum information tasks. His current research interests include quantum resources, optical and atomic implementations of quantum information tasks and protocols, quantum computing, mathematical modeling, computational intelligence, and machine learning. In 2015, he received the Sultana Nahar’s Prize for the best Ph.D. thesis in Egypt. In 2017, he also received a scholarship as a Visiting Researcher with the University of Oxford, U.K. In 2017, he has been elected as a Junior Associate Member of the African Academy of Science, Kenya. He is acting as a Managing Editor of some journals, such as *Information Sciences Letters* (Scopus), *Quantum Physics Letters*, and the *International Journal of New Horizons in Physics*.

ASHRAF KHALIL received the Ph.D. degree in computer science from Indiana University, USA, and has published notable research on ubiquitous computing, social and mobile computing, bioinformatics, persuasive computing, and human–computer interaction. The results of his research have been published through the top conferences in the fields, such as CHI, CSCW, and INTERACT. He is currently a Professor with the College of Technological Innovation, Zayed University, United Arab Emirates. Previously, he served as a usability consultant for major companies, such as Nokia, HSBC, Samsung, and Microsoft. He has authored over 50 publications in top journals and conferences and achieved numerous accolades, including many research grants from ADEK, the Emirates Foundation, and Google. He is interested in applying diverse technological innovations to address pertinent problems.

MAHMOUD ABDEL-ATY received the Ph.D. degree in quantum optics from the Max Planck Institute of Quantum Optics, Munich, Germany, in 1999, and the D.Sc. degree in 2007. He is currently the Director of the International Relations Center, Sohag University, Egypt, and the former Vice President of the African Academy of Sciences and the Dean of Research and Graduate Studies at Applied Science University, Kingdom of Bahrain. After his analytical study of quantum phenomena at Flensburg University, Germany, he joined the Quantum Information Group in Egypt. He is especially well-known for his seminal contributions to theories of quantum measurement, nanomechanical modeling, highly nonclassical light, practical information security, and optical implementations of quantum information tasks. His current research interests include quantum resources and optical and atomic implementations of quantum information tasks and protocols. His research has been widely recognized and he has received several local and international awards. He obtained the Amin Lotfy Award in Mathematics, in 2003, the Mathematics State Award for Encouragement, in 2003, the Shoman Award for Arab Physicists, in 2005, the Third World Academy of Sciences Award in Physics, in 2005, the Fayza Al-Khorafy Award, in 2006, and the State Award for Excellence in Basic Science, in 2009. In 2014, he was elected as the Vice President of the African Academy of Science. In 2016, he was elected as a member of the governor council, GC, of the Egyptian Mathematical Society.

HICHEM ELEUCH received the Diplom-Ingenieur Univ. degree in electrical and information engineering from the Technical University of Munich, in 1995, and the Ph.D. degree in quantum physics from the Kastler Brossel Laboratory, École Normale Supérieure de Paris (ENS) and Université Pierre-et-Marie-Curie (Sorbonne University), Paris, France, in 1998. He is currently a Professor of physics with the University of Sharjah, United Arab Emirates. He has worked at and visited several prestigious universities and research institutes, including Texas A&M University, the Max Planck Institute for the Physics of Complex Systems, Princeton University, McGill University, The University of Auckland, and the University of Montreal. He has published more than 200 articles in peer-reviewed international journals and holds three U.S. patents. He has participated in over 70 international conferences and given more than 40 invited talks. He has refereed articles for more than 50 physics journals (*Nature Communications*, *Scientific Reports*, and *Physical Review Letters*) and mathematics journals (*Applied Mathematics and Computation* and the *Journal of Mathematical Physics*). His research interests include quantum optics, quantum computing, matter-radiation interactions, low-dimensional quantum systems, mathematical physics, and complex systems. He also reviewed work for MITACS (a Canadian funding agency). He has successfully supervised and graduated more than 15 (Ph.D. and M.Sc.) students and also monitored several postdoctoral fellows. He has been awarded several fellowships (from the Fulbright Foundation, Max Planck Society, and the International Center of Theoretical Physics, Trieste, Italy). He is also a fellow of the African Academy of Sciences as well as a member of the Mohammed bin Rashid Academy of Scientists.

• • •