**Two-qubit quantum logical gates based on QND interaction between twisted light and atomic ensemble.**

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The development of protocols and algorithms for quantum computing is a challenge for the scientific community today. The spatially multimode twisted light with orbital angular momentum (OAM) could be considered as interesting object to study for several reasons. The OAM of light can take any integer value, which gives us an unlimited information resource [1]. Light with OAM shows high stability when propagating in a turbulent atmosphere, so it has a relatively high (relative to light without OAM) decoherence time [2]. Since we consider well-localized spatial modes, there are experimental techniques for generating [3], separating, and detecting such multimode radiation [4].

There are two fundamentally different approaches when constructing the theory of quantum computing using the quantum states of light - these are calculations in discrete and continuous variables. Calculations in discrete variables use the discrete degrees of freedom of a photon as a resource, for example, polarization (which encodes the state of a binary logical object - a qubit) [5] or the orbital angular momentum of light (OAM) (which encodes a multidimensional logical state - a qudit) [6]. To construct an arbitrary unitary computational operation in discrete variables, we should be able to perform at least two one-qubit (single-qubit) operations and one two-qubit controlled operation [7]. However, the creation of a two-qubit controlled quantum gate is a difficult task, since photons do not interact directly, and complex devices proposed for this purpose have a rather low probability of success [8].

In our work [9] we proposed a method for realization of quantum single qubit gates, as well as generalized qubit protocols to systems of higher dimensionality - qudits. We also investigate the possibility of constructing a two-qubit logical transformations. Successful attempts have been made to build single-qubit quantum logic gates over single photons possessing OAM [10, 11]. At the same time, the construction of two-qubit gates over qubits encoded through states of optical fields is a nontrivial task due to the lack of direct ( non-mediated) interaction between the light states.

 As a logical transformation for study we chose *SWAP* [12] element, which in qubit representation describes cyclic permutation of states of two qubits, and is an integral part of quantum computing. For example, *SWAP* gate is an important component of the network scheme of Shor’s algorithm [13]. In addition, it is shown that the ability to successfully implement a logical SWAP transformation is a prerequisite for the network compatibility of quantum computation [14]. It is important to note, that, given the way to perform the SWAP gate, we could also obtain two-qubit entangling gate $√SWAP$.

In our work we propose to consider quantum non-demolition (QND) interaction [15] between an ensemble of cold atoms and multimode light with OAM as one of the possible ways to implement a quantum gates in discrete variables. We demonstate that the system under consideration allows one to perform *SWAP* and $√SWAP$ operation on several two-qubit systems simultaneously, which is undoubtedly an advantage in solving the scalability problem.

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[1] Allen L. et al. Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes //Physical review A. – 1992. – Т. 45. – №. 11. – С. 8185.

[2] Li S. et al. Atmospheric turbulence compensation in orbital angular momentum communications: Advances and perspectives //Optics Communications. – 2018. – Т. 408. – С. 68-81.

[3] Xiao Q. et al. Generation of photonic orbital angular momentum superposition states using vortex beam emitters with superimposed gratings //Optics express. – 2016. – Т. 24. – №. 4. – С. 3168-3176.

[4] Dai K. et al. Measuring OAM states of light beams with gradually-changing-period gratings //Optics letters. – 2015. – Т. 40. – №. 4. – С. 562-565.

[5] Barrett S. D., Kok P. Efficient high-fidelity quantum computation using matter qubits and linear optics //Physical Review A. – 2005. – Т. 71. – №. 6. – С. 060310.

[6] Gottesman D. Fault-tolerant quantum computation with higher-dimensional systems //NASA International Conference on Quantum Computing and Quantum Communications. – Springer, Berlin, Heidelberg, 1998. – С. 302-313.

[7] Deutsch D. E., Barenco A., Ekert A. Universality in quantum computation //Proceedings of the Royal Society of London. Series A: Mathematical and Physical Sciences. – 1995. – Т. 449. – №. 1937. – С. 669-677.

[8] Nemoto K., Munro W. J. Nearly deterministic linear optical controlled-NOT gate //Physical review letters. – 2004. – Т. 93. – №. 25. – С. 250502.

[9] E. Vashukevich, E. Bashmakova, T. Y. Golubeva, and Y. M. Golubev, High-fidelity quantum gates for oam single qudits on quantum memory, Laser Physics Letters 19, 025202 (2022).

[10] A. Babazadeh, M. Erhard, F. Wang, M. Malik, R. Nouroozi, M. Krenn, and A. Zeilinger, Highdimensional single-photon quantum gates: concepts and experiments, Physical review letters 119, 180510 (2017).

[11] X. Gao, M. Krenn, J. Kysela, and A. Zeilinger, Arbitrary d-dimensional pauli x gates of a flying qudit, Physical review A 99, 023825 (2019).

[12] C. M. Wilmott and P. R. Wild, On a generalized quantum swap gate, International Journal of Quantum Information 10, 1250034 (2012).

[13] A. G. Fowler, S. J. Devitt, and L. C. Hollenberg, Implementation of shor’s algorithm on a linear nearest neighbour qubit array, arXiv preprint quant-ph/0402196 (2004).

[14] L.-m. Liang et al., Realization of quantum swap gate between flying and stationary qubits, Physical Review A 72, 024303 (2005).

[15] K. Hammerer, A. S. Sørensen, and E. S. Polzik, Quantum interface between light and atomic ensembles, Reviews of Modern Physics 82, 1041 (2010).