

QUANTUM COMPUTER

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Scalable optical quantum computer

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Abstract. **A way of designing a scalable optical quantum computer based on the photon echo effect is proposed. Individual rare earth ions Pr^{3+}, regularly located in the lattice of the orthosilicate (Y_2SiO_5) crystal, are suggested to be used as optical qubits. Operations with qubits are performed using coherent and incoherent laser pulses. The operation protocol includes both the method of measurement-based quantum computations and the technique of optical computations. Modern hybrid photon echo protocols, which provide a sufficient quantum efficiency when reading recorded states, are considered as most promising for quantum computations and communications.**

Keywords: *photon echo, quantum computer, quantum computations.*

1. Introduction

Photon echo (PE) and similar nonlinear optical phenomena, which make it possible to manipulate quantum states of physical objects, are considered as a promising physical basis for developing quantum communication and quantum computation protocols [1, 2].

To date, a large amount of experimental data on a wide class of PE-related phenomena have been accumulated. PE is observed in atomic ensembles, liquids, molecules, impurities in solids, thin polymer films [3 – 5], etc. Modern PE protocols make it possible to control signals with high accuracy.

PE applications are developed simultaneously in two directions: for quantum storage and for quantum calculations. The property of PE to retain and then reproduce the signal shape allows one to use it naturally in optical memory devices. The possibility of recording, storing for a sufficiently long time and exactly reconstructing the initial signal is especially urgent for operation with quantum states of the electromagnetic field. The possibility of copying a state of this field with its subsequent transfer is an important factor for quantum computers, because it allows one to perform auxiliary operations of computational cycle without data loss. The corresponding time delay makes it possible, in particular, to perform necessary data preparation or post-processing.

To design a prototype of a quantum computer capable of carrying out a large volume of computations, one must have two (as a minimum) matched devices with a high quantum efficiency: quantum memory and quantum register. The main function of the quantum memory is to store quantum states transferred by an electromagnetic field. The quantum register, composed of a set of quantum keys, is intended for data processing [6].

In terms of quantum efficiency, experiments with superconducting quantum dots, microcavities and ion traps [1, 2, 7] can be considered to be the most successful approaches to implement quantum computations. However, all the aforementioned realisations can hardly be scaled; therefore, the problem of increasing the computational power of a quantum computer remains open. The development of an experimental setup, sufficiently complex even for implementing only quantum memory, calls for technical solutions that cannot be provided by modern technology. Nanoscale solid-state technologies allow one to construct quantum computers from scalable blocks, which are suitable for quantum processing. The use of solid-state devices is also promising from the applied point of view: to match quantum memory and quantum register. Thus, development of the PE-based optical quantum computer architecture is an urgent problem for quantum computations and optics.

In this paper we analyse the possibility of using PE and optical manipulations with quantum objects as a physical basis for a scalable quantum computer.

PE application protocols for quantum memory [8, 9] are expected to increase the quantum efficiency and simultaneously implement parallel data processing. These results, obtained for different media, including gases, optical fibres and thin polymer films [10], significantly expand the experimental base for quantum manipulations.

2. Technology of optical computations

To date, different ways of designing an optical computer have been proposed [11, 12]. Nonlinear-optics technology (NLOT) has been developed within the PE approach. It is based on a vector-matrix multiplier (VMA), which performs classical computations only via operations with an optical field [11]. NLOT makes it possible to implement all operations performed by a classical computer: data storage, processing, erasure and transfer. The specific features of the physical mechanism of PE formation allow one to perform not only summa-

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tion but also multiplication of bits during one computational cycle on a crystal, which additionally increases the operating speed of an optical echo processor. In a wide class of media exhibiting the PE effect orthosilicate crystals doped with rare-earth ions are promising for optical data processing. When using NLOT, data are recorded by laser pulses and processed on rare-earth ions Pr^{3+}, incorporated into a Y_2SiO_5 matrix. Orthosilicate matrices are chosen due to their high optical durability, a feature making it possible to use them as scalable blocks in real computations, which call for processing large numbers of laser pulses per unit time.

The PE-based optical memory involves the same principles as an optical processor. However, to increase the data storage time, one should use more efficient cooling. For example, signal storage times of ~24 h were obtained for modern phase memory devices. Studies aimed at forming PE at room temperature are under way. Progress in this field would make it possible to develop a material base for commercial prototypes of optical-computation systems.

Based on the optical-computation technology, it is proposed to implement not only optical but also quantum data processing using PE-based modern protocols, including hybrid ones. The idea is to construct a scalable quantum register based on the architecture of a vector-matrix multiplier with a pixel structure. One pixel contains one rare-earth ion, the levels of which are used to model a qubit. The use of F states of rare-earth elements allows one to apply different techniques of quantum manipulations (including, in particular, the PE effect) due to the large number of energy levels and transitions between them.

3. Measurement-based quantum computations

One of the most efficient approaches is the organisation of optical measurement-based quantum computations (MQCs). An example is a unidirectional quantum computer [6, 13, 14]. A qubit array prepared in the entangled cluster state is used in MQCs. In the two-dimensional case this array forms a square lattice, on which the specified algorithm is implemented via only single-qubit measurements in the adaptive basis.

In contrast to the quantum-chain model, where quantum computations are performed through unitary operations, in the case of MQCs, the data are processed by a sequence of single-qubit measurements. Here, the universal (i.e., algorithm-independent) resource is the two-dimensional cluster state.

Computations are performed as follows (Fig. 1). A two-dimensional cluster state $|C\rangle$ of sufficiently large size is prepared in the initial state. There are isolated qubits at the input of a computational register, to which the input data on the program and the data on processing are supplied. A sequence of adaptive single-qubit measurements M on the chosen qubits is performed. The adaptivity implies computation of the basis of each subsequent measurement in dependence of the result of the previous measurement (note that recomputation can also be performed on a classical computer). In the course of computations, the nature of which is nondeterministic, the number of entanglements decreases. When all measurements are finished, the system is in the state $|\xi^\alpha\rangle|\psi^\alpha_{\rm out}\rangle$, where the superscript α characterizes the set of measurements over all measurement branches. The $|\psi^\alpha_{\rm out}\rangle$ states over all branches are equivalent to the desired output state (accurate to the Pauli operator). The measured qubits are in the $|\xi^\alpha\rangle$ state, which, in turn, depends on the measurement results at

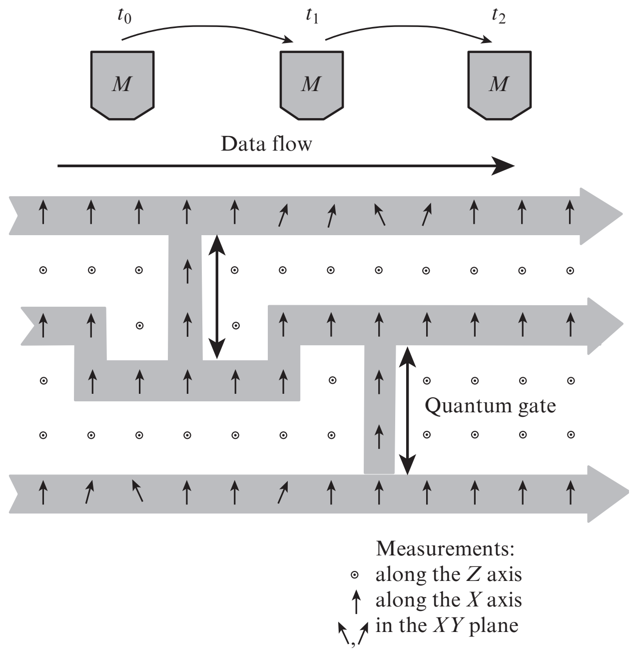

Figure 1. Measurement-based quantum computations (MQC).

the output. The last measurement is performed on the output qubit and contains the computation result. An important feature of this technique is the rigorous priority (time sequence) of measurements.

To date, the validity of the MQC method has been confirmed in some experiments, where photons played the role of qubits. This approach imposes certain limitations on the construction of deterministic quantum keys. In our opinion, a more promising way is to use a combination of linear optical methods and circuits with material qubit carriers [15].

4. Optical quantum computer

Let us consider a physical realisation of a qubit as a set of isolated energy levels of a rare-earth ion, where the optical field frequency is in resonance with the ion spectra of F electrons. As for any two-level system, we can introduce a pseudospin, as in the case of nuclear magnetic resonance (NMR). Then we will compare the evolution of an optical pseudospin in the course of logical operations with a qubit. Under the conditions of single-photon resonance, we consider impurity ions as a two-level system, which is described in terms of the Bloch equations. The ground state $|0\rangle$ corresponds to the Bloch vector directed upwards along the Z axis (Fig. 2).

The strict upward direction of the Bloch vector corresponds to the excited state $|1\rangle$. Hence, one can easily see that any state in the form $|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$, where $|\alpha|^2 + |\beta|^2 = 1$, is a possible pure state of a pseudospin.

All necessary unitary transformations of a qubit will be performed by means of optical π and $\pi/2$ pulses, as in classical PE protocols. The couplings between spins, which are necessary to form a logic gate, are implemented due to the dipole–dipole interaction between neighbouring pseudospins. To continue the analogy with NMR, the dipole–dipole interaction can be considered as an Ising one: $H_{\rm int} = C\sigma_z^{(1)}\sigma_z^{(2)}$ [13]. The use of $\pi/2$ pulse transforms the entire system of optical qubits (which are initially in the ground state) into a set of

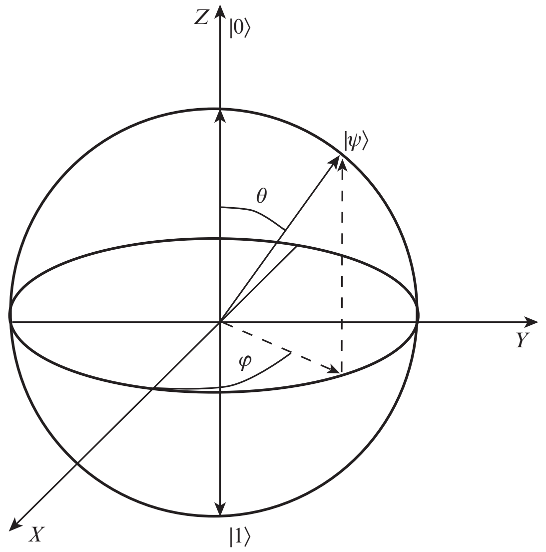

Figure 2. Bloch sphere.

coherent superposition states $|\pm\rangle$ with a probability of 1/2. Then the cluster obtained is subjected to single-qubit measurements according to the MQC method.

The advantage of PE over other physical realisations (e.g., neutral atoms captured into optical two-dimensional traps) is the larger number of addresses for effects on an individual qubit. This is obtained at a corresponding distribution of optical qubits in the orthosilicate crystal matrix and under effect of spatial optical modulators on these qubits. In the case of PE, these operations can be performed not only successively but also simultaneously. For simultaneous computations, we can place no more than one emitter in a region on the order of the focusing spot area; due to this, individual addressing of each qubit is obtained. Modern experimental techniques expand the PE classical version by involving all atoms contributing to the inhomogeneously broadened resonant line. This circumstance can be considered as an additional resource in the formation of independent computational channels. It is known that in the classical case PE is observed on a macroscopically large number of oscillators; however, this is not a hindrance to use the PE effect for operation with individual quantum states. For example, it is proposed to use PE and similar effects to prepare the initial cluster state $|C\rangle$, on which computation is performed. When preparing a new computation cycle, one must also ensure the possibility of erasing recorded data; incoherent light can be applied to this end.

All operations with qubits must be performed for a time shorter than the phase memory time τ_0. The yield of one computation channel at an optical pulse duration $\tau_i \simeq 10$ fs is $1/\tau_i \sim 10^{14}$ bit s^{-1}. One can increase the data flow density using different frequencies of optical resonances. On the assumption that $N_{ch} \sim 10^7$ channels with a channel size of ~10 μm can be formed on a square plate with a size of 3.5 cm, the maximum yield in the multichannel mode (with allowance for parallel processing) can be estimated as $N_{ch}\tau_i \sim 10^7 \times 10^{14} = 10^{21}$ bit s^{-1}.

To use PE in quantum computations, one must make data reading more reliable than for classical protocols. The purpose of developing new hybrid techniques (protocols) of the PE formation [9] is to increase the quantum efficiency of reading recorded states. One of the approaches aimed at reducing the influence of quantum noise is the active mechanism of rephasing (AMR protocol), in which atomic coherence is rephased using nonresonant interaction with a control laser field [9]. The AMR protocol allows one to solve the problem of spontaneous transitions, thus improving the quality of the signal yielded by rephasing.

Currently different ways to increase the quantum efficiency and noise stability have been actively discussed [16]. The use of three-dimensional quantum keys (i.e., topological methods of quantum computations) with post-processing increases the stability to errors.

5. Conclusions

The proposed protocol of operation of an optical quantum computer according to the MQC algorithm can be implemented based on NLOT. It is proposed to use individual rare-earth ions (Pr^{3+}), regularly located in an orthosilicate crystal (Y_2SiO_5), as optical qubits. The PE-based technology can be applied in both the upgraded version, with adaptation to individual quantum objects, and directly, for intermediate classical computations.

The advantage of NLOT based on solid-state nanoscale technologies over the schemes based on cooled atoms in a three-dimensional optical trap is the larger number of addresses, which is provided by the more free position of atoms. One can operate with quantum objects (qubits) using hybrid schemes, including linear optical methods. In this case, two matched devices with a high quantum efficiency (quantum memory and quantum register) operate according to different principles, forming, nevertheless, a single whole. Then the quantum states located in the quantum memory will be transferred by the electromagnetic field to the quantum register, composed of a set of data-processing quantum keys.

It is proposed to perform quantum computations using the MQC method, where data are processed by a sequence of adaptive measurements of individual qubits. Here, the algorithm-independent computational resource is the two-dimensional cluster state.

All operations with qubits that are necessary for quantum computations can be carried out using coherent and incoherent laser pulses. Intermediate classical computations can be performed by means of NLOT, which increases significantly the operating speed due to the use of optical computations and also diminishes the sizes of the system. A possible solution to the problem of decoherence, which is general for all real physical devices modelling a quantum computer, is to reduce to effect time on a qubit. If this time is shorter than the phase memory time τ_0, data processing is finished before the onset of the recorded state decay.

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