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Optical control system for quantum bit emulator based on green laser, AOM modulators and FPGA technology

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Abstract

Scientists involved in building quantum computers are currently facing many physical difficulties. Creating qubits, manipulating them and reading their state requires a lot of experience. This paper describes an optical laser system as a test platform for quantum-optical control that enables effective manipulation of an emulated quantum bit. Importantly, it is a reproduction of the system controlling the optical path in real ion traps. This solution makes it possible to study the phenomena occurring in such systems and to learn about the wide range of problems that a designer and an operator of quantum systems may encounter, even before they start building them. The optical system presented in the article uses, among others, a 532 nm laser, acousto-optic modulators (AOMs), ultrafast light detectors, and a programmable FPGA chip. The entire optical system was then attached to the QUBIT emulator and thoroughly tested. The article describes the design and operation of the proposed optical system and shows an example of how to control it using a Python script.

1. Introduction

The modern world is striving very hard to create a fully functional quantum computer [1], which, as we know, operates on completely different principles compared to a classical computer. Unlike classical computers based on a set of bits, a quantum computer works on the basis of a set of quantum bits called qubits. A qubit is represented by a state vector in a two-dimensional complex Hilbert space [2]. Qubits differ from classical bits in the way they encode and process information, offering capabilities that go beyond what is possible with classical bits. The classic bit can take only one of two discrete states: '0' or '1'. The qubit, on the other hand, is not limited to being in just one of the two basis states, denoted $|0\rangle$ and $|1\rangle$. Instead, it can be described by a general quantum state that combines these basis states with certain complex-valued coefficients. Upon measurement, the qubit yields one of the two outcomes - $|0\rangle$ or $|1\rangle$ - with probabilities given by the squares of the magnitudes of these coefficients, such that the total probability is always equal to 1. We refer to such a combination of basis states as a superposition. The qubit retains its quantum nature until it is measured, at which point its state collapses to one of the basis states, effectively behaving like a classical bit. In addition, a qubit is also characterised by a relative phase between the components $|0\rangle$ and $|1\rangle$, which plays a crucial role in the qubit evolution under the influence of the Hamiltonian system [3]. The current state of the qubit, i.e., its phase and superposition, can be represented graphically by two angles θ (THETA) and ϕ (PHI) on the Bloch sphere Fig. 1.

In real quantum systems, the values of these angles can be set with appropriate and precise pulses of, for example, laser light. In general, in many quantum systems, the formation and application of laser pulses is a very important way to control various internal quantum states [4–8]. By choosing the power of the laser, its wavelength and duration of the pulse, such a control system can be tuned and the expected effects can be obtained. The practical usability

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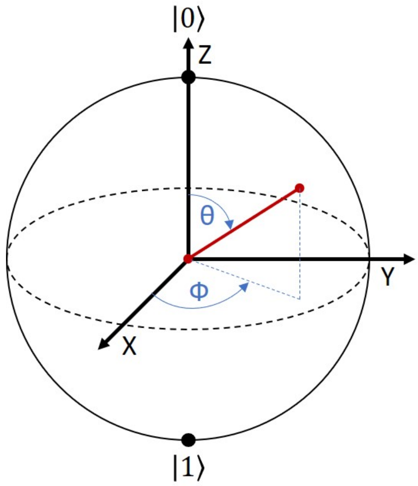

Fig. 1. The Bloch sphere.

of such a solution then depends to a large extent on timing and amplitude precision of the formation of the pulses themselves, as well as the ability to deal with unpredictable disturbances that may arise spontaneously. The importance of laser stability and precise control of the optical pulses was also discussed in more recent implementations of laser qubit control systems [9, 10].

Building a quantum system with the potential to become a quantum computer is not a simple undertaking. The challenge of creating a suitable set of stable qubits is only one of the difficulties that emerge. Another, perhaps even bigger problem arises when we want to control individual qubits. Unwanted quantum phenomena, internal noise of the system, electromagnetic interference from the environment, imperfection in the materials and components used, improper procedures for forming control pulses, or various types of operator errors – means we have to deal with a whole avalanche of difficulties and issues related to the stability of the system and the repeatability of the implemented operations when developing such systems [11]. All such problems should be addressed and researched to a large extent even before building practical quantum systems [12], as lack of adequate knowledge and skills, as well as unintentional mistakes, can result in large financial losses and can ultimately lead to discouragement of the builders themselves. So, before we start building actual expensive quantum systems, it is a good idea to create a suitable physical model of the quantum system and practice some aspects of qubit control on it beforehand. This will allow us to gain practical experience and seek methods of dealing with possible problems that arise in such circuits and systems.

This paper describes a test platform for quantum-optical control as a practically realised hardware emulation of qubit manipulation using laser light pulses. Here, a previously developed quantum bit emulator implemented on the basis of an FPGA [13] and controlled only by digital electrical pulses was used as a qubit. On the other hand, the process of controlling the qubit with a laser itself was realised with a real optical system based on acousto-optic modulators (AOMs) and two high-speed light detectors. AOMs allow the formation of short microsecond pulses of real laser light of a user-specified duration.

2. Preparing the QUBIT emulator to respond to pulses of laser light

The object controlled by the system described here is an off-the-shelf, previously realised QUBIT emulator [13] created on the basis of an FPGA chip. This emulator represents a qubit by means of a Bloch sphere displayed on a monitor screen Fig. 2.

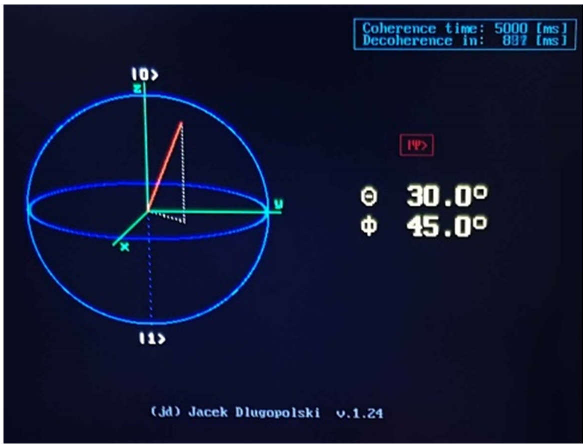

Fig. 2. The QUBIT screen.

The state of the qubit is therefore determined by two angles: θ (THETA) and ϕ (PHI). The THETA angle determines the superposition level and the PHI angle determines the phase of the modeled qubit $|\psi\rangle$, according to the formula (1):

$$|\psi\rangle = \cos\frac{\theta}{2}\,|0\rangle + e^{i\phi}\sin\frac{\theta}{2}\,|1\rangle. \tag{1}$$

As in real quantum systems, the values of THETA and PHI angles here cannot be set directly. The user can only set the initial state of the entire qubit to $|0\rangle$, and then, using a series of electrical pulses of specific lengths, must make the appropriate rotations of the qubit state vector so as to obtain the intended new qubit state. Control pulses must be formed with an accuracy of 1 µs. Schematically this is shown in Fig. 3.

In order to make it possible to control the qubit with pulses of laser light, a suitable circuit was built to convert the light pulses into proper electrical pulses. High-speed specialised Hamamatsu S10317-1 detectors [14] were used for this purpose. This is shown schematically in Fig. 4.

After such modification, the QUBIT can be controlled by pulses of laser light. However, what is required is the ability to form pulses of light of micro- and millisecond lengths with an accuracy of 1 µs. The Hamamatsu S10317-1 detectors selected and used here have good enough performance to cope with proper conversion of this type of light pulses. These parameters are shown in Fig. 5.

In order to achieve such fast conversion of laser light pulses into corresponding electrical pulses, a special module with laser light detectors was designed in Fig. 6(a) and physically built in Fig. 6(b).

Once the module is connected to the QUBIT emulator, the emulator is able to respond correctly to the controlling pulses of laser light and it is then possible to optically manipulate its quantum state.

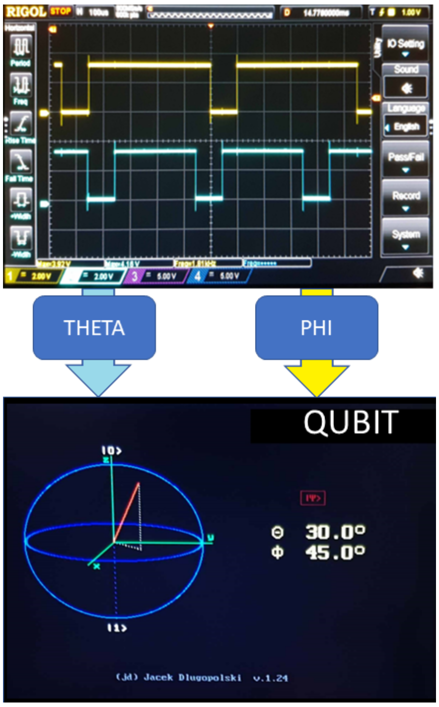

Fig. 3. Electrical control of the QUBIT [13].

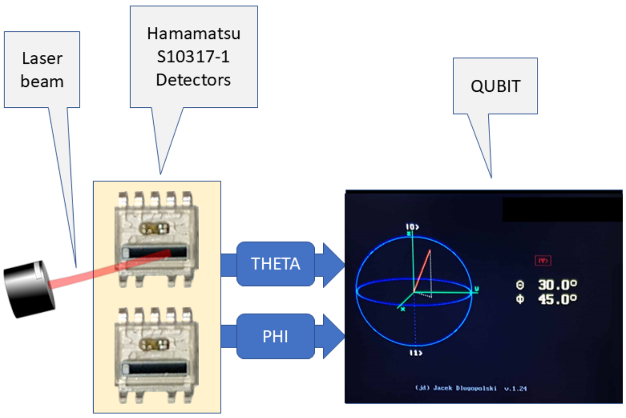

Fig. 4. The QUBIT optic control system.

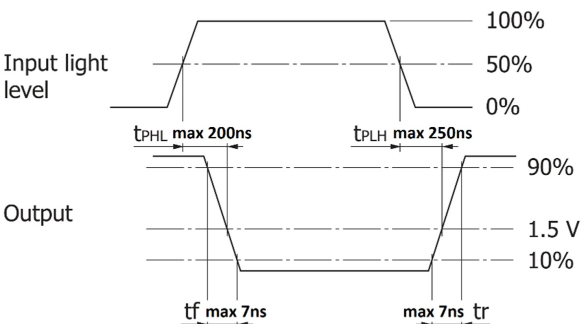

Fig. 5. Time parameters of the S10317-1 detector [14].

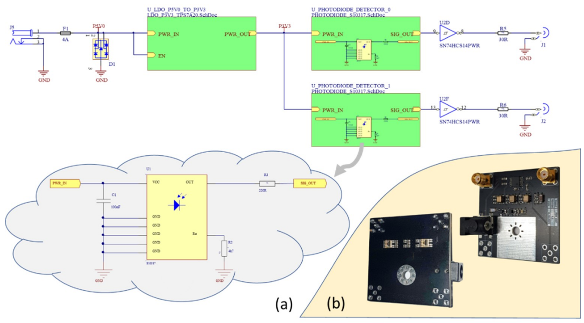

Fig. 6. Electronic schematic of the laser light detection module (a) and photos of the physical device made (b).

3. Optical laser light pulse formation system

In order to control a properly prepared qubit emulator with a laser, it is necessary to build two cooperating optical blocks: an optical pulse-forming block and an optical detector-addressing block. Both optical blocks are based on their own AOM modulator and its driver, and are controlled using GENMET, built on a high-speed FPGA programmable chip. Among other things, the GENMET device performs the electrical pulse generation functions needed here and is described in detail in the QUBIT emulator paper [13]. The electrical pulses generated by GENMET are used to control the AOM modulators that form precise pulses of laser light and to properly deflect the laser beam to address the correct detector (THETA or PHI). The designed optical system is shown schematically in Fig. 7.

The light emitted by the laser goes through the absorptive filter and then through the $\lambda/2$ wave plate to clean the polarisation and set it to the desired linear orientation. Then light passes through polarising beam splitter (PBS), AOM1, $\lambda/4$ wave plate (changing the polarisation to circular), and collimating lens. Then the undesired diffraction orders are being blocked and the desired one is being reflected by mirror, upon which the polarisation is being rotated by 90° hence switching it to a circular direction opposite to the incoming beam. The returning beam passes second time through the lens and quater-wave plate on which the polarisation is again changed but now from circular to the linear – which results in the beam being perpendicularly polarised to the incoming beam. The laser beam then passes through AOM1 once again and is then reflected by the PBS and guided to AOM2. After passing through AOM, the unused diffraction order is being blocked while the useful ones are being guided to designated light detectors.

The fragment built on the AOM1 works in a double-pass arrangement and allows the laser light beam to be switched on and off very quickly and efficiently. This makes it possible to form pulses of light with an accuracy of the required one microsecond. On the other hand, the second part of the circuit built on the AOM2 is used to quickly address one of the two detectors mounted on the control inputs of the QUBIT emulator. The correct use and positioning of the mirrors here effectively separates the first- and second-order beams, allowing them to hit the THETA and PHI detectors with ease. At any given time, one can control only one parameter of the emulated qubit, i.e., making either a change in the THETA angle or a change in the PHI angle.

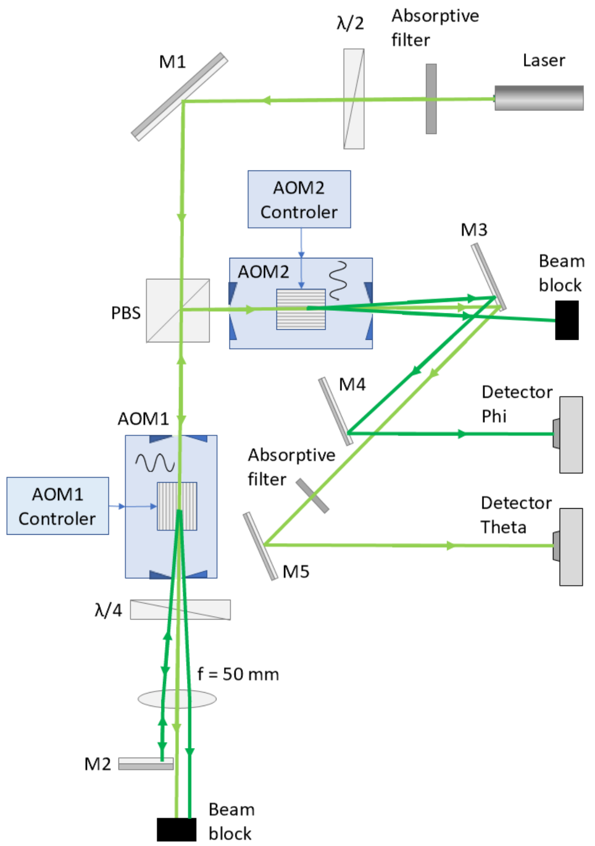

Fig. 7. Schematic of an optical system with a double-pass circuit for forming laser light pulses and addressing light detectors. $\lambda/2$ – half-wave plate, M1,M2,..,M5 – mirrors, PBS – polarising beam splitter, AOM1(2) – acousto-optic modulator 1(2), $\lambda/4$ – quater-wave plate, f = 50 mm – lens with focal length of 50 mm.

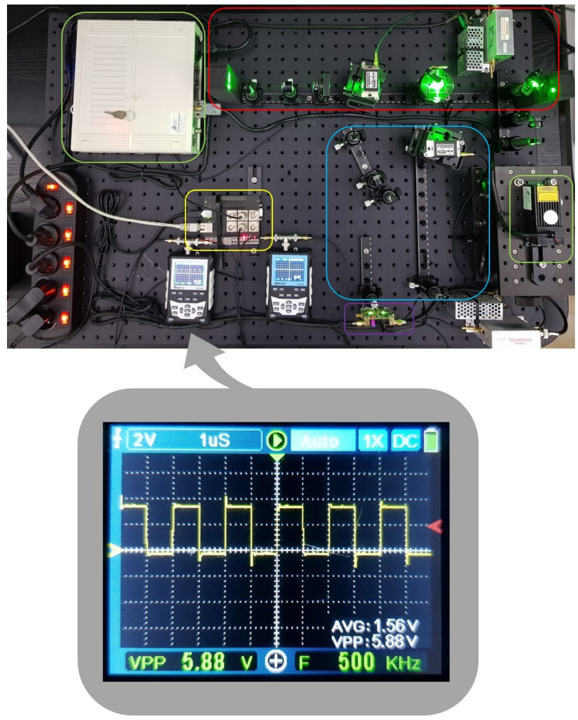

Fig. 8. The assembled optical system with an FPGA-based device for forming pulses of laser light.

4. Proof of concept

In order to examine the concept of the laser pulse control system for the Qubit emulator described above, the entire optical system was assembled, checked and finally connected to the QUBIT emulator, and then the whole thing was practically tested. The most significant components employed in the construction of the entire prototype system are as follows:

- 1 x QUBIT emulator [13]
- 1 x DPSS 532 nm Green Laser SDL-532-300T [15]
- 2 x AOM [16]
- 2 x AOM-controller [17]
- 2 x Light detector [14]
- 1 x GENMET generator [13]

The final result of the assembled optical system is shown in Fig. 8.

The laser and its power module have been circled with a green line. A 532 nm laser was chosen because of its relatively low cost, high availability, and ease of optical system assembly, as green light is easily detectable by the human eye. Unfortunately, most lasers used to manipulate qubits in real ion traps are often expensive or operate in wavelengths invisible to the human eye, which makes optical setup alignment difficult and also increases its cost due to the price of optical components. Therefore, we had to choose a different wavelength in order to demonstrate proof of concept at a relatively low cost. Another important factor was the performance of the AOMs used with 532 nm light, high diffraction efficiency at lower RF powers compared, for instance, to red or infrared wavelengths. The red line marks the AOM-based optical double-pass path used to form pulses of laser light. The blue line indicates the AOM-based optical path for addressing the detectors. In contrast, the detectors themselves are marked with a purple line. The device controlling the two AOMs, based on a programmable FPGA chip, is marked with a yellow line. The photograph also shows two oscilloscopes connected to both detectors. During system testing, these oscilloscopes were used to check the correct length of the formed pulses and the correct deflection of the laser beam to both detectors.

In Fig. 9 presented below, the designed optical system (top) controls the QUBIT emulator (below on the right). The two light detectors were connected via shielded cables with SMA connectors to the respective THETA and PHI inputs of the QUBIT emulator. As already mentioned, an FPGA-based GENMET [13] device is used to control the AOM modulators. Two output channels of the device (OUT1 and OUT2) are used here. The OUT1 channel controls the AOM1 modulator and is used to key the laser beam to form pulses of light of the desired length with an accuracy of one microsecond. The OUT2 channel, on the other hand, controls the AOM2 modulator and is used for splitting and deflecting the laser beam to effectively address the selected light detector. This enables independent control of the THETA angle or PHI angle in the connected QUBIT emulator.

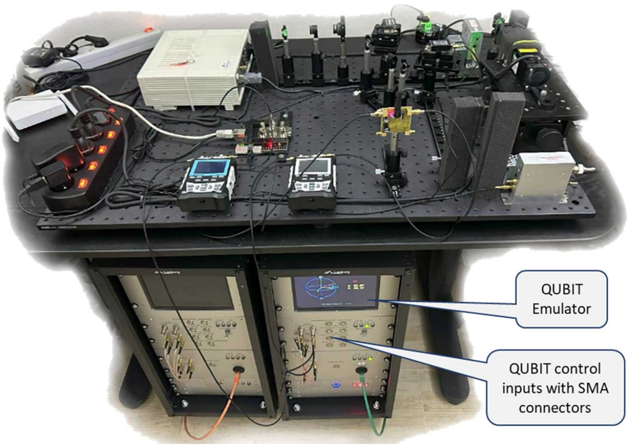

Fig. 9. The prototype of the laser control system.

For example, to set the state of the qubit to THETA = 46° and to PHI = 75°, the following steps must be performed in the emulator:

- Turning off the active signal to AOM1 to disable the laser beam in the double-pass circuit.
- Turning off the active signal to AOM2 to set the THETA detector addressing.
- Generating with AOM1 a pulse of laser light with a duration between 9000 µs and 9100 µs to reset the THETA angle to zero, that is, to set the qubit into the quantum $|0\rangle$ state.
- Generating a 460 µs pulse of laser light with AOM1 to change the THETA angle of the state vector by 46°.
- Enabling the AOM2 constant active control signal to set the PHI detector addressing
- Generating with AOM1 a pulse of laser light with a duration between 9000 µs and 9100 µs to reset the PHI angle (qubit phase) to zero.
- Generating a 750 µs pulse of laser light with AOM1 to change the PHI angle of the state vector by 75°.

An example Python script that implements the above sequence is shown in Fig. 10.

The upper part of the script is the appropriate preparation of the socket for sending user datagram protocol (UDP) type packets to the GENMET device controlling the AOM

```
# (jd)
import socket
s=socket.socket(socket.AF_INET, socket.SOCK_DGRAM)
s.setsockopt(socket.SOL_SOCKET, socket.SO_BROADCAST, 1)
def snd(data):s.sendto(bytes(data+" ","utf-8"), ("10.0.0.255", 12000))
##################################################


# Set QUBIT to THETA= 46°  and PHI=75°

snd(" genmet7 start [us] nr 0 low1 400 high1 0 ")        # turn off laser beam

snd(" genmet7 start [us] nr 0 low2 400 high2 0 ")        # choose THETA detector
snd(" genmet7 start [us] nr 1 low1 400 high1 9010 ")     # reset qubit THETA angle to 0
snd(" genmet7 start [us] nr 1 low1 400 high1 460 ")      # increase THETA angle by 46°

snd(" genmet7 start [us] continuous low2 0 high2 400 ")  #  choose PHI detector
snd(" genmet7 start [us] nr 1 low1 9 high1 9010")        # reset qubit PHI angle to 0
snd(" genmet7 start [us] nr 1 low1 400 high1 750 ")      # increase PHI angle by 75°
```

Fig. 10. Python script to set qubit to THETA = 46° and PHI = 75°.

modulators. The lower part of the script, on the other hand, implements the sending of UDP packets initiating the creation of a series of laser pulses sent to the corresponding detectors to set the QUBIT emulator into the required quantum state.

The laser control of QUBIT tests has yielded positive results, thus confirming the validity of the concept presented here. The pulses of laser light produced by the built optical system allow the THETA angle and PHI angle to be changed with an accuracy of 0.1° and therefore allow any operation to be performed on the controlled qubit.

Achieving an angular precision of 0.1° requires a good quality laser with minimal fluctuations and also thermal stability in all the optical and electronic components. The components used in the described platform provide the above-mentioned conditions. It is also important to ensure low and stable external lighting because it affects the operation of optical sensors. In this case, it is the user's responsibility to provide a suitable space for experiments.

5. Conclusions

The system described in this article is sensitive to thermal and lighting conditions, among other things. External lighting affects the operating thresholds of the optical sensors, so it is important to minimise external light intensity and ensure that it remains constant during experiments. Thermal stability must also be considered. The setup achieves full thermal stability approximately 15 minutes after powering up. However, these aspects are advantageous here because, as mentioned above, similar problems are encountered in laser systems that control real quantum installations. Observing these dependencies on the test platform prepares users for the problems they will face when controlling qubits in a real ion trap.

Therefore, the concept presented in this article of controlling the QUBIT emulator using pulses of laser light can provide a very interesting platform to gain the necessary basic experience even before building the final quantum systems. The features of the QUBIT emulator itself, equipped with functions for applying internal and external noise to the current state of the qubit and functions for emulating the decoherence phenomenon, now further supplemented by the ability to form laser control pulses, provide a substantial opportunity for initial insight into the problems of controlling quantum systems and how to deal with them.

The tests carried out on the built system showed its proper operation. With a single laser, it is now possible to control two independent parameters of the qubit, and this is done with very short pulses of laser light, as is the case in many real-world quantum systems. Future upgrades to the proposed optical system are planned, for example, to enable control of more than one qubit. In that case, however, it will be necessary to replace the AOM modulator, used here to address the detectors, with an acousto-optic deflector (AOD), which allows the laser beam to be freely deflected over a wider range. Therefore, with AOD, we would be able to address more detectors. For example, the ability to address four detectors would allow us to effectively control two qubits. Such an upgrade will therefore make it possible to build laser-controlled quantum emulators for multiqubit systems, and thus also allow testing of multiqubit quantum gates. It is worth mentioning that such solution was also already tested and implemented in the real ion trap-based quantum computer [18]. Thus, use of AODs in the future in the upgraded version of developed platform can be considered fair and reasonable in order to better understand the setups used in real quantum computer projects.

The platform presented in the paper allows for the control of two parameters (THETA and PHI) of a single qubit. Only one of them can be controlled at a time. It is not possible to control both parameters simultaneously, due to the use of only a single laser. Implementation of controlling both parameters simultaneously would require adding another laser or splitting the main laser beam, which would significantly increase installation costs. Each additional qubit adds two more parameters to control, requiring two additional independent laser beams and two AOMs. With a larger number of qubits, this approach would not be economically viable. It would also be difficult to implement in practice, if only because of the size of the lasers and optical path components.

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