SIMULATIONS OF THE POLARIZATION DEPENDENCE OF THE LIGHT POTENTIAL EQUATION IN QUANTUM COMPUTING

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ABSTRACT

Many methods of quantum computing are currently being researched because quantum computers may be able to perform certain calculations that we currently cannot because they would take the age of the universe. To create a viable quantum computer one must be able to create a multiple qubit gate. For our specific approach, neutral atom quantum computing, one must find a way to bring two atoms together, entangle them and separate them in order to create a multiple qubit gate. In our research we explored a way of facilitating the creation of a multiple qubit gate using the diffraction pattern created by two polarized lasers incident upon a

pinhole. We found that it may be possible to create moveable atom traps using this approach and thus it may be possible to create multiple qubit gates using this approach.

INTRODUCTION

Quantum computing is being researched because in theory quantum computers can perform certain calculations much faster than a conventional computer. While a conventional computer's most basic components are bits, a quantum computer's most basic components are quantum mechanical bits also known as qubits. Quantum mechanical bits can be made from any quantum mechanical particle, such as atoms, electrons and photons. The big difference between a qubit and a classical bit is that while a bit can be either one or zero at any given time a qubit can be both one and zero at the same time. This property of qubits would allow us to store much more information on them than on a conventional bit which could lead to much faster computations of certain calculations.

Many methods of quantum computing are currently being researched. Some involve trapping quantum mechanical particles in solids and others involve trapping quantum mechanical particles using light [1]. There are advantages and disadvantages to all of the various methods being researched. Some, like three dimensional optical lattices have scalability, meaning that many qubits can be created and held together, but lack things like addressability and the ability to create multiple qubit gates [2]. In order to create a viable quantum computer all of these are necessary [3]. One must have scalability, addressability, and be able to create multiple qubit gates. Addressability is the ability to interact with an individual bit and is required in order to initiate calculations and read out of said calculation as well as implement gates. Scalability is necessary to attain a system with enough qubits in order to perform larger scale calculations. Multiple qubit gates are required in order to perform calculations that require multiple inputs and outputs. While multiple qubit gates have been created using nuclear magnetic resonance methods; this method currently lacks the scalability to perform larger scale calculations.

The specific approach we are exploring uses a few key properties of quantum mechanical particles and the effects of light polarization. The most mysterious of quantum effects that this approach exploits is entanglement. Entanglement is the linking of quantum mechanical particles through interaction. Two atoms that have been entangled can be separated a distance as large as the universe and yet what happens to one instantly happens to the other on the other side of the universe. Entanglement is required to create a viable quantum computer because without entanglement it would be impossible to link two quantum mechanical particles and thus impossible to create a multiple qubit gate.

The second key property of quantum mechanical particles that we exploit is superposition. Quantum mechanical particles can be in a combination of internal states at the same time. Superposition is the idea that these states can be combined to form an overall state that can be normalized to one. As applied to quantum computing this means that the total internal state of a qubit can be broken into two parts that can be used to represent the two states of a quantum computer. A few examples of how this is mathematically possible are shown in Figure 1.

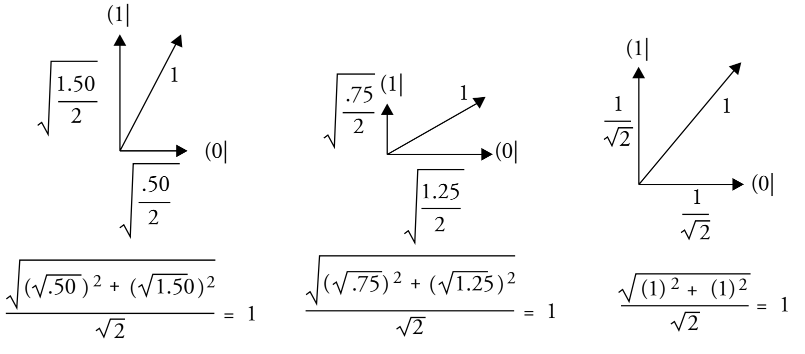

Figure 1. A simple example of how superposition works in which all vectors are normalized to 1.

The final physical property we are trying to exploit is light polarization. Light can propagate in a number of ways. Light can be linearly polarized, circularly polarized, elliptically polarized or a mixture thereof. Linearly polarized light propagates in such a way that if you were to look at the line traced out by the electric field vector it would appear to form a straight line. As circularly polarized light propagates the electric field vector appears to trace a circle. This is because as the electric field vector is composed of two electric fields that are exactly 90 degrees out phase and have the same magnitude. Elliptically polarized light is created in two ways. One way is similar to the way circularly polarized light is created. There are two electric field vectors that are exactly 90 degrees out of phase; however, the two electric fields are not the same magnitude. This results in the overall electric field vector appearing to rotate and change length such that the overall electric field vector appears to trace out an ellipse. Another way that elliptically polarized light can be created is if the electric field vectors are anything but 90 degrees out of phase, regardless of their magnitude. This results in the overall vector tracing out an elliptical pattern. These types of polarizations are shown in Figure 2. [4].

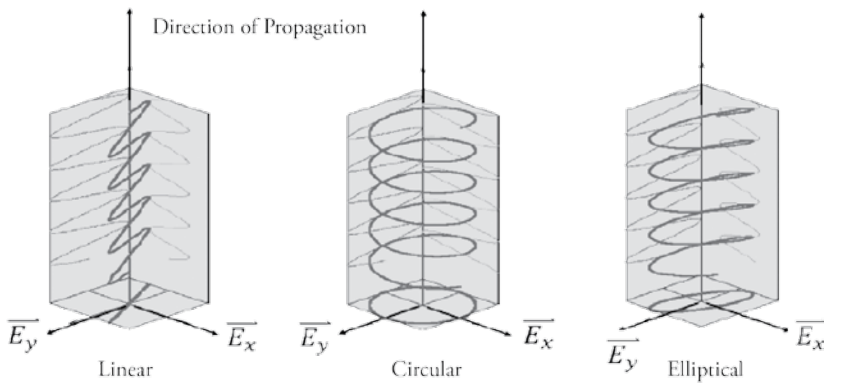

Figure 2. Examples of how the various polarizations of light propagate [4].

In this project, we are exploring the possibility of facilitating multiple qubit gates using a method similar to the three-dimensional optical traps mentioned earlier [2]. Currently, we are exploring the possibility of creating three dimensional optical traps using lasers that are incident on a pinhole. When lasers are incident upon a pin hole they create diffraction on the other side of the pinhole. An example of this diffraction pattern is shown in Figure 3 [5].

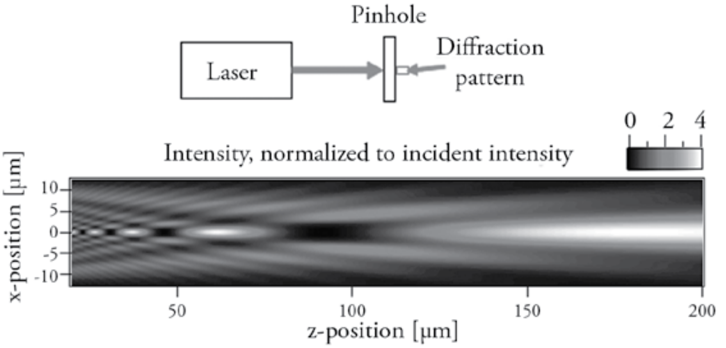

Figure 3. The diffraction pattern created by light incident on an aperture [5].

We are exploring the possibility of creating two different traps in the same intensity pattern using lasers of different polarization that are going through the same pinhole (see Figure 4). This looks very similar to the above trap; however, it has two dark spots instead of one. Since atoms can be in polarization sensitive states it may be possible to create two traps that contain atoms of different internal states that can be moved using the angle between the two lasers. One problem that arises when bringing traps together is that contents of each trap can move from one trap to the other. In this approach, this is not a concern because the atoms are in polarization sensitive states and are trapped using polarized light. This means that if two traps were brought together, the contents of each trap would not go into the other because they are only sensitive to the trap created by one specific polarization of light.

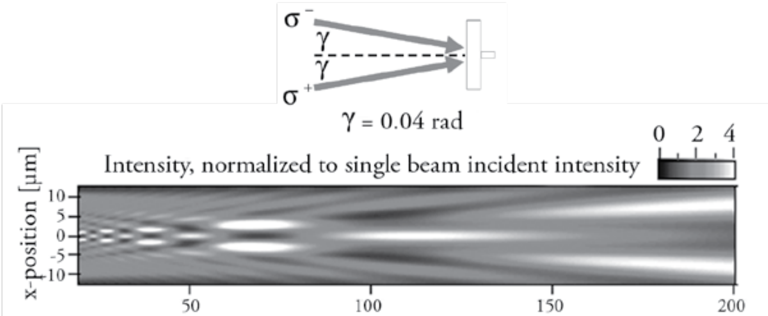

Figure 4. Diffraction pattern created by two lasers of different polarization incident on a pinhole

THEORY

We began with the compact form of the light potential equation shown in Figure 5. First we derived the explicit form of the light potential equation (shown in Figure 6) and then programmed it into Mathematica so that we could use the program to simulate various optical traps.

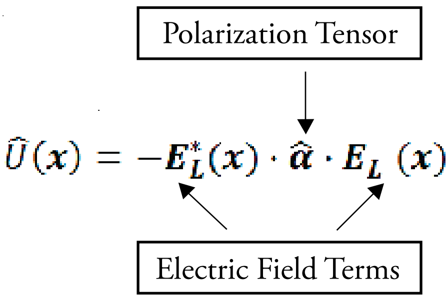

Figure 5. The compact form the light potential equation [6].

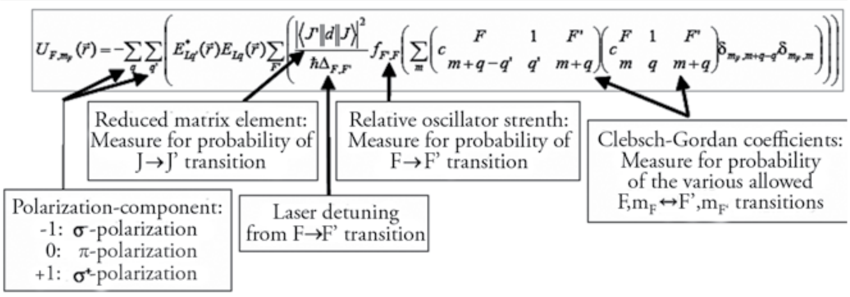

Figure 6. The explicit form the light potential equation and explanations of terms [6, 7].

METHODS

We programmed the explicit form the light potential equation into Mathematica in order to solve the light potential equation much more easily. Using this program we can generate simulations much more quickly and spend more of our time coming up with light traps that we can simulate. After performing our test case, we had to modify the code to accept the electric fields as a table of information rather than a mathematical function. This is because we received the electric field data as a list of data from Dr. Glen Gillen rather than representing the electric fields as functions. We chose to model the fields this way because the diffraction pattern is very complex and cannot be represented as a function. Using our code and the electric field data we were able to calculate the trapping potential of the diffraction pattern due to the pin-hole for several incident laser beam angles.

RESULTS

During this quarter we further developed the code required to simulate the trapping potentials of very complex light patterns such as diffraction patterns. Using this code we were able to simulate the trapping potential of the diffraction pattern created when one left-circularly polarized laser (σ_-) and one right-circularly polarized laser (σ_+) are incident upon the same pin-hole. Our overall goal was to investigate the possibility of trapping and manipulating the locations of two different atoms in the same intensity pattern using the polarization dependence of optical traps. Figures 7 and 8 show the intensity patterns as well as the trapping potentials seen by each atom, one in $m_F = +1$ and one in $m_F = -1$, of two differently polarized lasers incident upon a pinhole. Figure 7 shows the trapping potential for a small angle between the two lasers (γ=0.02 radians) and Figure 8 shows the trapping potential for a large angle between the two lasers.

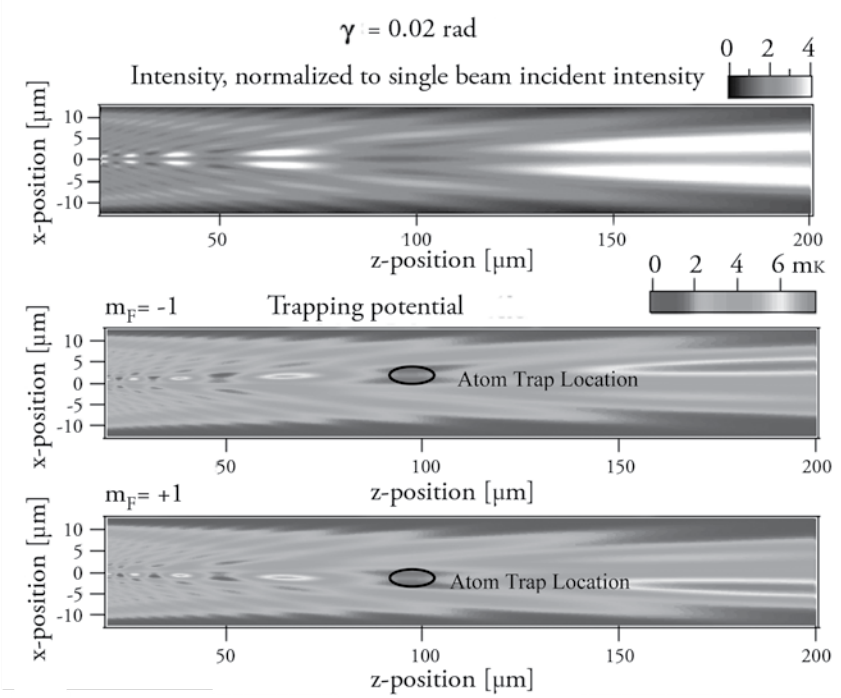

Figure 7. The intensity pattern and trapping potentials for a small angle (γ=0.02 radians) between the two lasers.

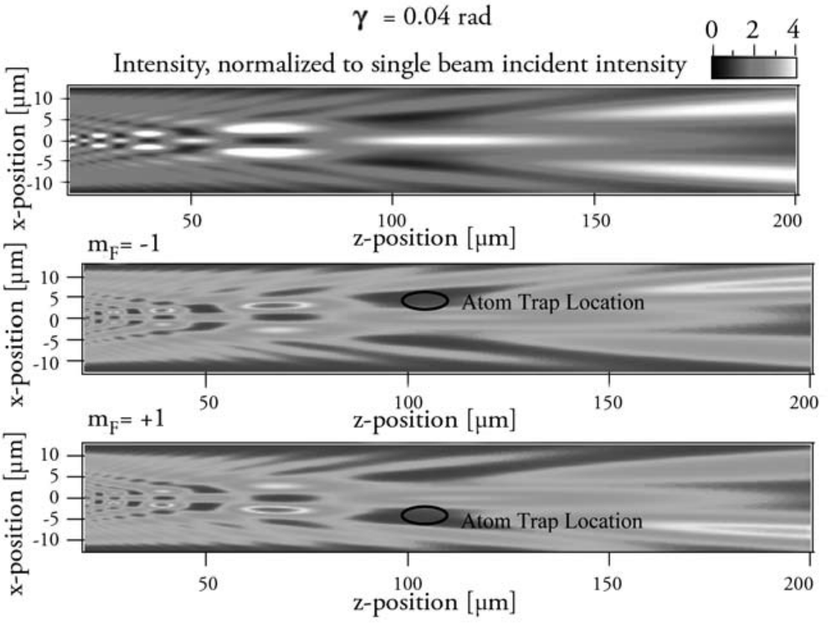

Figure 8. The intensity pattern and trapping potentials for a large angle (γ = 0.04 radians) between the two lasers.

The two trapping potential diagrams shown under each intensity pattern can be thought of as being right on top of each other. The larger dark blue spots are where we are planning on trapping atoms. For the diagram of the smaller angle the two traps are very close together. This means that the two can be brought very close together without the atoms jumping from one trap to the other. In Figure 8 the traps are starting to get relatively far apart. This means that the two traps can be brought together and apart by changing the angle between the two lasers being used to create the trap, which in turn means that the two atoms can be brought together, be entangled and then separated creating a two qubit gate.

CONCLUSION

It may be possible to create light traps that can be used to manipulate the location of atoms using the diffraction pattern created by two differently polarized lasers incident upon a pinhole. Using this approach it may be possible to create a multiple qubit gate using neutral atoms, the holy grail of neutral atom quantum computing.

We recently presented these findings at the annual meeting of the Division of Atomic, Molecular and Optical Physics at Pennsylvania State University. Our findings were well received among the scientific community and the simplicity of the approach was liked by all. Currently our future plans consist of setting up a lab in which to experimentally test the feasibility of this approach in practice.

WORKS CITED

[1] R.Grimm et al. "Optical dipole traps for neutral atoms" Adv. AMO Phys., 42 (2000), 95-170

[2] I. H. Deutsch et al. "Quantum Computing with Neutral Atoms in an Optical Lattice" Fortschr. Phys. 48 (2000) 9-11, 925-943

[3] D. P. DiVincenzo, "The Physical Implementation of Quantum Computation" Fortschr. Phys. 48 (2000) 9-11, 771-783

[4] "Polarization Diagram." 18 May 2008. Online image. Wikipedia. 1 June 2008. <http://en.wikipedia.org/wiki/Polarization>.

[5] G. D. Gillen, et al. "Optical dipole traps for cold atoms using diffracted laser light" Physical Review A 73 (2006), 013409

[6] I.Deutsch et al. "Quantum-state control in optical lattices" Phys. Rev. A, 57 3 (1998), 1972-1986

[7] M. Tinkham, "Group Theory and Quantum Mechanics", 1964