LIGHT TRAP MANIPULATION AND ITS POTENTIAL USE IN QUANTUM COMPUTING

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EXECUTIVE SUMMARY

During winter quarter 2007, the light polarization dependence of light traps used in quantum computing was researched. Throughout the quarter, a Mathematica program that simulates the trapping potential of light traps was modified; it now takes into account the polarization of light used, as well as the internal state of the atoms used in the light traps. The goal for the next quarter, spring 2007, was to use the program that was generated to simulate the trapping potentials of traps of varying parameters. This research was conducted to deduce whether there is any possible way to implement the light polarization dependence of light traps in quantum computing. More specifically, the intent was to investigate potential ways to create a two-qubit gate using the light polarization dependence of the light traps.

INTRODUCTION

Last quarter, a Mathematica program was generated to simulate the trapping potential of light polarization-dependent light traps used for trapping atoms for quantum computing. The program was tested by using it to calculate the trapping potential of a basic lattice with known trapping potential; it attained the correct result. This research is a continuation of Professor Gillen's doctoral research, which explores the use of two-dimensional light traps as a basis for quantum computing. The goal of this research is to use the Mathematica program generated to simulate light traps of varying parameters to attempt the construction of the holy grail of quantum computing: a two-qubit gate.

BACKGROUND

Before the quest to research the possibility of a two-qubit gate was begun, there was a significant amount of research involved essential to understanding the theory behind quantum computing. First, a qubit is similar to a bit of a conventional computer in the respect that it is the smallest functional part of a quantum computer. In conventional computers, the bits can be linked to form multiple bit gates, which allow for multiple inputs and outputs into a calculation. In quantum computing, multiple bit gates have the same function: they allow for multiple inputs and outputs into and out of a calculation. Single qubit gates have been made; however, multiple qubit gates, or more specifically, two-qubit gates, have not been created. Two-qubit gates are sought after because they would allow for a quantum computing system to function at its full potential.

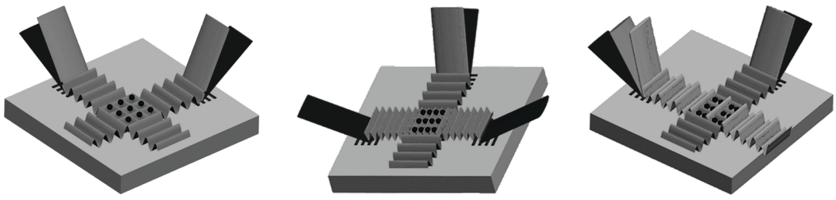
A qubit is the abbreviation of "quantum mechanical bit" and includes any quantum mechanical particle, such as a photon, an electron, or an atom, that can be used as a basis for quantum computing. However, instead of being initialized strictly to a state of one or zero as a standard bit is, a qubit can be initialized to any combination of both one and zero, as stated by the principle of superposition.

Using the principle of superposition in conjunction with the principle of entanglement, it may be possible to create a two-qubit. Entanglement is a mysterious property of quantum mechanical particles in which they can link their internal states through various particle interactions. After the two particles become entangled, they can be separated an infinitely large distance. If the internal state of one particle changes, the internal state of the other will change as well [4]. This effect may allow us to link two atoms in the quantum computing system, enabling us to form a two-qubit.

Another important concept to this research is light polarization. Light polarization is the pattern that the electromagnetic field lines in a light wave trace out as the light wave propagates. The electromagnetic field vectors of light can form three distinct patterns while propagating: linear, circular, and elliptical. The electromagnetic field vectors in linearly polarized light simply move up and down as the light travels through spaces, whereas the electromagnetic field vectors of circularly-polarized light rotate as the light wave travels through space. The electromagnetic field vectors of elliptically-polarized light will rotate while propagating; one of the vectors will be shorter than the other, resulting in an elliptical cross section. This phenomenon is being used in the light traps to determine whether there is a way to use the polarization of light to manipulate the light traps in such a way as to create two-qubit quantum.

There are three light traps that are to be manipulated using the polarization of the lasers used in the traps: a basic two-dimensional lattice, a counter-propagating lattice, and a three-mode lattice (all depicted in Figure 1). Each consists of the same basic set-up of laser incident from different directions. However, the three-mode lattice has an extra laser of varying power coming in from one direction. The counter-propagating lattice is distinctive because it has two of its lasers coming in from opposite directions rather than the same direction. Using these traps, atoms can be contained in specific locations. Next, using lasers from above, the atoms can be initialized, read from, and written to.

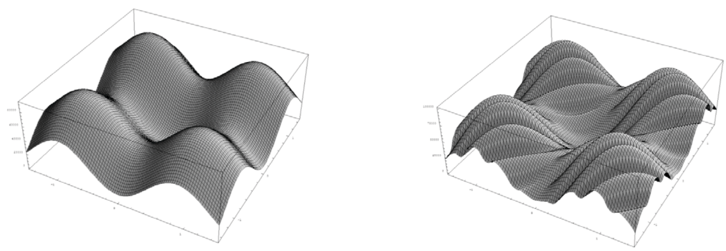
The developments from last quarter gave us the ability to manipulate the lattices using the light polarization of the lasers used in the lattices. Using laser light polarization in conjunction with other parameters in the light traps, it may be possible to controllably bring two atoms together with the intention of causing entanglement within them in order to a create two-qubit gate.



A B C

Figure 1. Picture A depicts the basic two-dimensional lattice. Picture B depicts the counter-propagating lattice. Picture C depicts the three-mode lattice [1].

Using lattices of varying parameters, there is the potential to create an array of qubits and two-qubits that may be manipulated in such a way that they can be used in an analogous manner to a conventional computer.



A B

Figure 2. A. A 3D graph of the trapping potential of a polarization insensitive state from last quarter. B. A 3D trapping potential graph of a polarization sensitive state from last quarter.

THEORY

Atoms of specific internal states will respond differently to different polarizations of light, and a light polarization that has an affect on one atom may not affect another atom at all [5,6]. This phenomenon would allow atoms of different internal states in their respective traps to be brought relatively close to one another, allowing the atoms to become entangled without risking potential escape from their respective wells. Using this in conjunction with the idea that the lattice can be manipulated by changing various parameters of the light trap, two separate light traps of different polarizations could be brought close enough together to allow the atoms contained in said traps to entangle and form a two-qubit quantum.

METHODS

The calculations for trapping potential are very complex, so they were solved using a math program called Mathematica. During Professor Gillen's doctoral research, she wrote a code that calculates the trapping potential for an atom trapped in lattice composed of linearly-polarized light [1]. This term is called the scalar trapping potential and it is displayed in equation 1.1[7].

$$U(\mathbf{r}) = \frac{2}{3}\frac{\hbar\Gamma}{8}\frac{\Gamma}{\Delta}\left|\frac{E(\mathbf{r})}{E_{sat}}\right|^2 \quad (1.1)$$

During winter quarter 2007, the vector trapping potential term was added, equation 1.2, [2] to the original Mathematica code, resulting in equation 1.3 [1, 2].

$$U(\mathbf{r}) = g_{nuc}(L,S,J,i,F)m_f \frac{2}{3}\frac{\hbar\Gamma}{8}\frac{\Gamma}{\Delta}\frac{\mathrm{Re}[\mathbf{E}_0^*(\mathbf{r})]\times \mathrm{Im}[\mathbf{E}_0(\mathbf{r})]}{(E_{0,sat})^2} \quad (1.2)$$

(1.3)

$$U(\mathbf{r}) = \frac{2}{3}\frac{\hbar\Gamma}{8}\frac{\Gamma}{\Delta}\left|\frac{E(\mathbf{r})}{E_{sat}}\right|^2 + g_{nuc}(L,S,J,i,F)m_f \frac{2}{3}\frac{\hbar\Gamma}{8}\frac{\Gamma}{\Delta}\frac{\mathrm{Re}[\mathbf{E}_0^*(\mathbf{r})]\times \mathrm{Im}[\mathbf{E}_0(\mathbf{r})]}{(E_{0,sat})^2}$$

With this added term, the Mathematica code now takes into account the polarization the light used to trap it, as well as the specific internal state of the atom. After developing the program, it was tested by calculating the trapping potential of a basic two-dimensional lattice with known polarization dependence and attained the correct results [3].

Then, during spring quarter 2007, the code was modified again such that the scalar potential equation also takes into account the polarization of light. This effect is often falsely ignored because it is quite small compared to the other terms and has minimal effects. Once it was discovered that there were terms missing, they were added to the program. The scalar equation, 1.1, changes to equation 1.4 after adding the polarization terms that are generally ignored. [7].

$$U(\mathbf{r})_{Scalarlightpotential} = \frac{1}{3}\frac{\hbar\Gamma}{8}\frac{\Gamma}{\Delta_{2,F}}\frac{1}{E_{sat}{}^2}\left[\left|E_{\sigma^+}(\mathbf{r})\right|^2\cdot(2+g_f m_f) + \left|E_{\sigma^-}(\mathbf{r})\right|^2\cdot(2-g_f m_f)\right] + \ldots$$

$$\frac{1}{3}\frac{\hbar\Gamma}{8}\frac{\Gamma}{\Delta_{1,F}}\frac{1}{E_{sat}{}^2}\left[\left|E_{\sigma^+}(\mathbf{r})\right|^2\cdot(1-g_f m_f) + \left|E_{\sigma^-}(\mathbf{r})\right|^2\cdot(1+g_f m_f)\right]$$

(1.4)

With this term added, the code fully takes into account the polarization of light and forms a very accurate portrayal of the trapping potential of the light traps.

RESULTS

The result of the research this quarter was the discovery that the three main ideas for creating a two-qubit have fundamental flaws and will not work. Each of the three lattices were tested spring quarter 2007 by varying specific parameters of the light traps in ways that were thought to be conducive to the formation of a two-qubit gate.

Counter Propagating Lattice

The basic shape of the counter-propagating lattice looked promising for trapping atoms because it had well-defined wells. However, when an attempt to manipulate the lattice using its polarization dependence was made, nothing occurred because the areas where the atoms were supposed to be trapped had no electric field. This meant that the atoms could not be moved around.

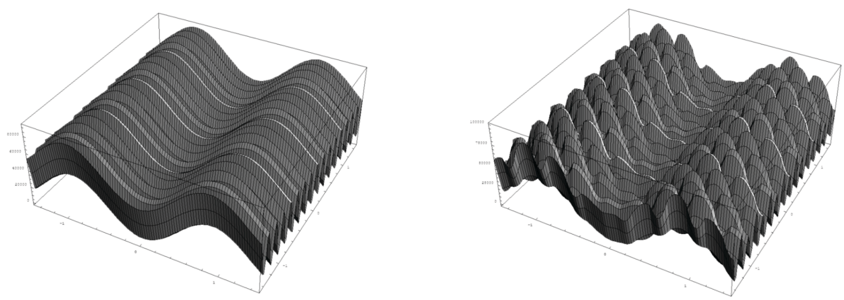
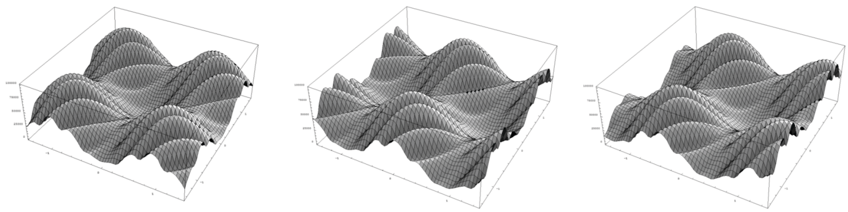


Figure 3. This figure depicts trapping potential of the counter-propagating lattice. Left is mf=1 and at right is mf = +1. This shows that an atom cannot be moved using this effect.

Basic Lattice

The basic lattice had the desired polarization effects. The lattices can be manipulated and also moved by changing the two relative phases. This would allow two atoms to be brought together and cause entanglement between them. However, the optical trap does not trap atoms very well. The ridges where atoms would be trapped only trap atoms in two dimensions, which means that they can fall out in the third dimension. Since the atom can fall out, this trap is not suitable for forming a two-qubit, even though the desired polarization effects were attained.

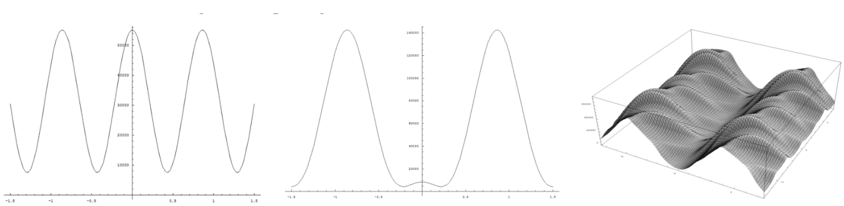


$\phi_{perp} = 0$ $\phi_{perp} = \pi$ $\phi_{perp} = 1.5\pi$

Figure 4. This figure depicts the motion of the trapping potential along the z-axes due to changing the angle of two waves incident from perpendicular directions in the basic two-dimensional lattice. It also depicts the lack of three-dimensional trapping at the top of the ridges.

Third Mode Power

Slowly adding in a third laser along the *z*-axis allowed a ridge to decrease out of the middle of the light trap in the three-mode lattice. Using this ridge, it may be possible to trap atoms in two separate wells and then bring them together by increasing the power of the third laser. Once the atoms meet, it may be possible to entangle and then separate them forming a two-qubit gate. This trap had the desired polarization effects, but it had the same problem as the two-dimensional lattice in that it does not provide three-dimensional trapping. This trap is also not suitable for forming a two-qubit gate.



$Power_{ThirdMode} = 0$ $Power_{ThirdMode} = .4$ 3D Plot

Figure 5. This figure depicts the dropping of the ridge in the middle of energy well as the power of the third mode increases.

CONCLUSION

In the research spring quarter 2007, the Mathematica code was further developed from the last quarter so that it now takes into account the polarization of the lasers used in the light traps. Once this was completed, an accurate code that worked correctly was available. Using this code, the parameters of the light traps were modified and three possible ways to create two-qubit, the overall goal of this research, were found. However, the three lattices used to create the two-qubit gates ended up being fundamentally flawed: either they do not provide enough trapping or they do not have the desired polarization effect.

This research was originally presented at the Department of Atomic Molecular and Optical Physics conference in Calgary, Alberta and after discussion, my peers agreed that the results did indeed make sense. The three potential ways that a two-qubit gate could be created were investigated; however, there are still many more possible ways that need to be researched. Currently, ideas for continuing this research are to perform the same simulations, but with an external electromagnetic field added in to determine how the external electric field may be used to manipulate the lattice. Professor Gillen also suggested that the code be modified so that it uses a different type of laser, which may affect the traps in other ways.

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