

SYSTEM AND METHOD FOR SPATIAL ADDRESSING OF INDIVIDUAL ATOMIC QUBIT

FIELD OF INVENTION

- 5 The present invention relates broadly to a system and method for spatial addressing of individual atomic qubit, in particular using the Kerr electro-optic effect.

BACKGROUND

- 10 Any mention and/or discussion of prior art throughout the specification should not be considered, in any way, as an admission that this prior art is well known or forms part of common general knowledge in the field.

- Quantum computing is considered to be an emerging technology with the potential to disrupt the supercomputing landscape. One of the front-running platforms to perform quantum computing is based on trapped and laser cooled ions. Two of the internal energy states of the ion act as a quantum bit (qubit) while an array of such qubits forms a quantum register. A set of operations using laser fields either on individual ions or two ions simultaneously form a universal set of gates to implement any quantum algorithms in the context of universal quantum computing. It has been shown theoretically that certain quantum algorithms can outperform currently used classical algorithms in speed, resource and/or energy. The currently available best machines reside in research laboratories or in private companies like IonQ or Quantinuum (former Honeywell). The major limitation of these machines lies in the quantum gate errors restricting their use. One of the main challenges to implement one or two qubit gates in an ion trap quantum computer lies in the addressability of individual or group of ions (interchangeably called as qubits).

- 25 Embodiments of the present invention seek to address at least one of the above problems.

SUMMARY

In accordance with a first aspect of the present invention, there is provided a system for spatial addressing of individual atomic qubit comprising:

- 30 One or more optical elements for focusing a laser beam onto individual ions localized in an ion trap;

a Kerr electro-optic deflector for deflecting the focused laser beam relative to the individual ions; and

a drive circuit to drive the Kerr electro-optic deflector;

wherein the Kerr electro-optic deflector is configured to deflect the focused laser beam using voltage pulses applied by the drive circuit to an electro-optic material of the Kerr electro-optic deflector for Kerr effect led variation of the refractive index of the electro-optic material.

5 In accordance with a second aspect of the present invention, there is provided a method for spatial addressing of individual atomic qubit comprising the steps of:

focusing a laser beam onto individual ions localized in an ion trap; and

deflecting the focused laser beam relative to the individual ions using a Kerr electro-optic deflector,

10 wherein the deflecting of the focused laser beam comprises using voltage pulses applied to an electro-optic material of the Kerr electro-optic deflector for Kerr effect led variation of the refractive index of the electro optic material.

BRIEF DESCRIPTION OF THE DRAWINGS

15 Embodiments of the invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

Figure 1 shows a schematic drawing illustrating the experimental set-up of the qubit addressing prototype system according to an example embodiment implemented on a Ba⁺ ion quantum computer with a chain of trapped ions.

20 Figure 2 shows a schematic drawing illustrating a driving circuit for a deflector, according to an example embodiment.

Figure 3 shows portions of the simulated optical set up to compare between a deflected beam and an undeflected beam for ion addressing, according to an example embodiment.

25 Figure 4 shows a schematic diagram of a driving circuit coupled to a deflector, according to an example embodiment.

Figure 5 shows a plot of the Rabi frequency squared for different deflector voltages, according to an example embodiment.

Figure 6 shows a plot of distance moved by the laser beam at the ion position versus the voltage applied to the deflector, according to an example embodiment.

30 Figure 7 shows the measured Rabi frequency on the qubit transition for the deflected case, according to an example embodiment, versus the undeflected case.

Figure 8 shows repeated measurements of a Ramsey sequence for deflected beam case, according to an example embodiment, versus undeflected beam case.

Figure 9A shows the tomography of the qubit state in the x-axis of a Bloch sphere, according to an example embodiment.

Figure 9B shows the tomography of the qubit state in the y-axis of a Bloch sphere, according to an example embodiment.

- 5 Figure 9C shows the tomography of the qubit state in the z-axis of a Bloch sphere, according to an example embodiment.

Figure 10 shows the simplified internal energy level diagram of a singly ionized Barium ion with Zeeman splitting for only the $6S_{1/2}$ and $5D_{5/2}$ levels.

- 10 Figure 11 shows a schematic drawing illustrating a system for spatial addressing of individual atomic qubit according to an example embodiment.

Figure 12 shows a flow-chart illustrating a method for spatial addressing of individual atomic qubit, according to an example embodiment.

DETAILED DESCRIPTION

- 15 Embodiments of the present invention provide an alternative physical hardware and method to tackle the challenge of ion addressing. Currently, the devices that are widely used either commercial or in research for ion addressing fall under the following categories:

1. Acousto-optic type (acousto-optic deflectors [AOD])
2. Mechanical (micro-mirror deflectors [MMD])
- 20 3. Pockels effect or linear electro-optic type (Pockels electro-optic deflectors [PEOD])

Example embodiments of the present invention propose and demonstrate the use of quadratic electro-optic effect (Kerr Effect) in a Kerr electro-optic deflector [KEOD], to perform individual qubit addressing which can offer one or more of the following advantageous effects:

1. Small foot-print compared to existing solutions
- 25 2. Addressability of wider quantum register compared to existing solutions
3. Ultra-low addressability errors
4. Negligible power loss
5. Weak wavelength dependence compared to AODs

- 30 A device according to an example embodiment is described herein and integrated to a full-stack quantum computer to demonstrate the basic operations, quantify and benchmark the performance.

Spatial addressing system of individual atomic qubit according to an example embodiment

To perform universal quantum computing, single and two qubit gates are used. These gates are applied sequentially as per the instruction table from a quantum algorithm on various qubits in a quantum register. Therefore, qubit specific operations, also known as addressability of qubits, is an integral part of a universal quantum computer. Atom-based quantum computers can be operated in two modes, namely, frequency domain or spatial domain depending on the use of microwave or optical frequency, respectively. Spatial domain addressability is easier to scale-up as it does not depend on the available bandwidth of the electronics. For spatial addressability, an example embodiment uses optical Kerr effect to controllably deflect laser beams from one qubit to the other. Optical Kerr effect is a higher order electro-optic effect, proposed for the first time to solve the efficient addressability problem in an atom-based quantum computer, to the best of the inventors' knowledge. The electro-optic properties of any material can be approximately written as:

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$$n_{eo} \approx n \left[1 - \frac{1}{2} P n^2 |\vec{E}| - \frac{1}{2} K n^2 |\vec{E}|^2 \right] \quad (1)$$

where n_{eo} is the overall refractive index, n is the refractive index of the material without electro-optic effect, P is the Pockels coefficient, K is the Kerr coefficient and $\vec{E}$ is the applied electric field vector. Lithium Niobate (LiNbO_3 , LN) is the most used material, typically in crystal form, with high Pockels coefficient ($\sim 30 \text{ pm/V}$) and a relatively low Kerr coefficient ($1.6 \times 10^{-9} \text{ pm}^2/\text{V}^2$) [6]. Among materials that show optical Kerr effect, potassium tantalate-niobate ($\text{KTa}_{1-x}\text{Nb}_x\text{O}_3$, KTN) in crystal form is chosen in an example embodiment as it has a very high Kerr coefficient ($1.0 \times 10^{-2} \text{ pm}^2/\text{V}^2$ [4]) near the paraelectric Curie temperature. One of the main hindrances to the application as deflector or modulator in device applications is the difficulty to produce such materials, e.g. KTN crystals, reliably/commercially. However, the present inventors have recognized that the advantage that can be achieved using such materials as a deflector for spatial addressing of individual atomic qubit can outweigh that difficulty.

In addition, the typical electrical drive proposed to be applied to a Kerr effect-based deflector has been a regular sinusoidal signal used for scanning operations [3]. Deflection is achieved by first injecting charges into the crystal through a bias voltage. The additional injected charge carriers in the system then provide a linearly graded refractive index with respect to the distance from electrodes. Nevertheless, the scanning speed is limited by the mobility of the charge carriers (electrons in this case). To allow for faster scanning operations, a different model of scanning has been conceptualized and implemented [3]. Briefly, in [3] the idea is to periodically apply a low frequency DC bias to the crystal intermittently during a fast sinusoidal scanning operation. This operation injects charges into the crystal and the refractive index is changed by the locally „trapped“ charges that are injected into the crystal. This allows for a faster response of the electrons as compared to the previous scanning model. Nevertheless, the scanning operation is still a sinusoidal and periodic one.

However, for typical deflection/modulation operations in quantum computing, the signal usually comes in the form of a TTL (transistor-transistor logic) pulse and is typically aperiodic. In an example embodiment a unique electrical drive is provided which is capable of maintaining the charge distribution even under aperiodic pulse sequence with high repeatability as shown in the results presented herein for a prototype according to an example embodiment, making a Kerr effect-based deflector according to an example embodiment capable to solve the efficient addressability problem in an atom-based quantum computer. A generic example embodiment of this unique drive is presented in Figure 2. An Arbitrary Waveform Generator (AWG) (example waveform indicated at numeral 150) is amplified and connected to the AC port of a bias-T to generate the drive signal 152. A high voltage DC supply HV is also connected to the DC port of the bias-T to provide the bias voltage 154 as part of the drive signal 152 used for the operation of the Kerr electro-optic deflector according to an example embodiment. The drive signal 152 is used to drive the Kerr electro-optic deflector for tackling the addressability issue, as will be described in more detail below.

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The change in refractive index for a material with high Kerr coefficient can be derived from eq. (1) as:

$$\Delta n = n - n_{eo} = \frac{1}{2} K n^3 |\vec{E}|^2 \quad (2)$$

It has been recognized by the present inventors that, since the change in refractive index is now proportional to the square of the electric field strength, a greater sensitivity in the tunability of the refractive index is achievable which is used for deflection according to an example embodiment. The gain in the refractive index change Δn for linear (Pockels) and quadratic (Kerr's) electro-optic effect cannot be directly compared (see eq. (1)). However, considering a bias electric field $\vec{E}_{dc}$ on top of a small signal electric field $\vec{E}_{ac}$ ($|\vec{E}_{ac}| < |\vec{E}_{dc}|$), it is possible to e.g. compare the electro-optic effect between LN and KTN. In order to compare the Pockels and Kerr coefficients, both need to be expressed in terms of a single signal variable. One can re-write equation (2) as

$$\Delta n = \frac{1}{2} K n^3 (|E_{dc} + E_{ac}|^2) \approx \frac{1}{2} K n^3 |E_{dc}|^2 + K n^3 |E_{dc}| \times |E_{ac}| \quad (3)$$

wherein the first term has no AC dependence while the second term is the same as the Pockels effect but with an effective Pockels coefficient of $K|E_{dc}|$. This effective Pockels coefficient for KTN is nearly 2 orders higher than the Pockels coefficient of LN for a DC field of 100V/mm. Applying the same treatment to the case of 33BKNT as another example material, a DC field of 100V/mm would lead to an effective Kerr coefficient similar to the Pockels coefficient in LN. However, because there is a scaling of the effective Pockels coefficient with electric field strength, a DC field of 10000V/mm will allow for the same advantage over LN.

This gives an advantage over PEOs which utilize the Pockels effect to achieve deflection. To achieve this high electro-optic effect, the K which is a function of relative dielectric constant is temperature tuned according to Curie-Weiss law:

$$K \propto \epsilon_r^2 \propto \frac{1}{(T-T_{cp})^2} (4).$$

- 5 The last proportionality in eq. (4) comes from the fact that KTN is a paraelectric material. Therefore, close to the critical temperature (T_{cp}), where KTN becomes cubic paraelectric crystal ($\sim 40^\circ \text{C}$), the Kerr coefficient becomes very high near the phase transition. For other materials such as 33BKNT, the dielectric constant, which directly affects the Kerr constant, does not change beyond an order of magnitude [8] with temperature. Similarly, deflection angle
- 10 has been shown to have minimal changes with temperature in Lead Lanthanum Zirconium Titanate (PLZT) [7]. It is also noted that materials such as KTaO_3 can achieve relatively high Kerr coefficient up to $3.0 \times 10^{-3} \text{ pm}^2/\text{V}^2$ [11], noting that the required temperature to achieve that is at 4.2 Kelvins which is not typically practical for usage in a small scale KEOD.

- 15 As described herein, a Kerr electro-optic deflector according to an example embodiment is configured to deflect the focused laser beam using voltage pulses applied by the drive circuit to an electro-optic material of the Kerr electro-optic deflector for Kerr effect led variation of the refractive index of the electro-optic material, i.e. wherein the Kerr effect based variation of the refractive index of the electro-optic material is larger than the Pockels effect variation of the refractive index of the electro-optic material.

20 Experimental setup according to an example embodiment

In order to build and set the qubit addressing system, a standard bulk optics (Thorlabs), off-the-shelves electronics and custom-made driver electronics were used in an example embodiment. The qubit addressing system prototype is integrated into an existing quantum computer based on Ba^+ ion [1,2], to characterize its performance.

- 25 Figure 1 shows the experimental set-up of the qubit addressing prototype system according to an example embodiment implemented on the existing Ba^+ ion quantum computer with a chain of trapped ions e.g. 100(inset). Two of the lasers (493nm and 650nm, at numerals 130, 132) are focused into a vacuum chamber 102 onto the trapped ions e.g. 100 for Doppler cooling of the trapped ions by constantly exciting the $6S_{1/2} - 6P_{1/2}$ and $6P_{1/2} - 5D_{3/2}$ levels (as illustrated in
- 30 Figure 10). These same lasers 130, 132 are also used to fluoresce the trapped ions e.g. 100 for qubit state readout. A second 493nm laser path at numeral 136 is present to optically pump the ion into one of the two Zeeman levels of the $6S_{1/2}$ state. The 614nm laser 134 addresses the $6P_{3/2} - 5D_{5/2}$ levels and removes any state population in the $5D_{5/2}$ state to reset the ion's internal state. Finally, the 1762nm laser 104 is used to address the $6S_{1/2} - 5D_{5/2}$ levels which is also
- 35 called the qubit level. In the example embodiment, the deflection system according to an example embodiment is implemented on the optical path of the 1762nm laser 104.

The Ba^+ ion-based quantum computer implementation according to the example embodiment shown in Figure 1 uses two of the internal energy levels of barium ions e.g. 100($6S_{1/2}$ and $5D_{5/2}$)

similar to a '0' and '1' of a transistor in a classical computer to perform single qubit rotation or two qubit entangling gates for quantum computing. Ions e.g. 100 are localized in the ion trap inside the vacuum chamber 102 and the quantum gate is implemented by directing the 1762nm laser 104 beam onto the ion. The rate at which this gate can be implemented in the example embodiment is known as the Rabi frequency (Ω) and it is related to the intensity, I , of the laser 104 beam in the form $\Omega \propto \sqrt{I}$. The time that it takes for the qubit to flip from 0 to 1 is known as the π time and it is inversely proportionate to the Rabi frequency. In addition to qubit inversion, a superposition state can also be created in the example embodiment by performing a qubit rotation. This is achieved by shining the laser 104 on the ion e.g. 100 for half of the π time. In this state, the qubit is sensitive to any electromagnetic field fluctuations that can interact with it and an amount of wait time is chosen for the interaction/s to occur. A second $\pi/2$ pulse can then be applied, and one can make deductions about the fluctuations/changes during the superposition state. Such a sequence is known as a Ramsey sequence [5].

Qubit addressing setup prototype according to the example embodiment shown in Figure 1: The prototype system comprises a half waveplate 106 and polarizing beam splitter, PBS, 108 for making the light linearly polarized. It is then passed through a pair of lenses 110, 112 to match the laser 106 beam size to the crystal size in the deflector 114. A second pair of lenses 116, 118 is placed after the deflector 114 to increase the beam size of the output laser beam for better focus-ability into the ion trap. The laser beam then goes through another half waveplate 120 and polarizing beam splitter 122 to ensure the light is linearly polarized. A final lens 124 then focuses the laser beam onto the ion/s e.g. 100 in the trap. In such a set-up according to an example embodiment, an angular deflection of the deflector 114 will lead to a translation of the focused beam at the ion position as shown in Figure 3.

Figure 3 shows portions of the simulated optical set up to compare between a deflected beam (at numeral 200) and an undeflected beam (at numeral 202) for ion addressing. Left portion in Figure 3: Laser beam path right after deflector 114 and after first lens 116 (compare Figure 1). Right portion in Figure 3: Laser beam path after final focusing lens 124 (compare Figure 1).

With reference to Figure 4, the deflector drive 126 according to an example embodiment comprises two separate DC supplies 400, 402 (Delta Elektronika ES0300-0.45, Aim-TTi PLH250, respectively), a temperature controller 404 (Thorlabs TED200C) and a digital control 406 (Field Programmable Gate Arrays, FPGA) as well as other passive electrical components R1, R2, C1 that are assembled as depicted in Figure 4. The digital control/FPGA 406 sequences a list of TTL pulses corresponding to the experimental sequence which controls the on/off switching of different lasers in the existing Ba⁺ ion quantum computer. An output from the digital control/FPGA 406 is connected to a BS170n-Channel FET switch 408 which correspondingly changes the voltage on the deflector 114. The magnitude of the change is determined by the setting on DC supply 402 while the DC supply 400 maintains the bias voltage for the deflector 114 operation according to an example embodiment. The BS170 n-Channel FET 408 is used for switching in an example embodiment and R1, R2 and C1 were chosen to optimize the switching speed. To prevent undesired charge accumulation leading to a backlash

error in an example embodiment, the pulses are designed to perform symmetric negative voltage swing before getting back to original state. In this setup, DC supply 400 provides the high voltage 154 in Figure 2. The digital control 406, BS170 FET 408 and DC supply 402 provides the arbitrary sequence of pulses 150 in Figure 2. Such a setup according to an example embodiment allows the generation of substantially square pulses aligned to the deflection timings used for the experiment according to an example embodiment.

Results and Analysis according to an example embodiment

Before testing for the addressability of the ion, the deflector's 114 performance at the ion position was characterized with the current optical set up according to an example embodiment. To do that, the distance moved by the beam at the ion position is measured. This is done by varying the voltage of the DC supply 402 and measuring the Rabi frequency for different voltages.

Figure 5 shows a plot of Rabi frequency squared for different deflector voltages, according to an example embodiment. The laser beam is deflected by different amounts (via voltage) and the Rabi frequency at each of the different voltages are obtained. The result is a Gaussian beam moving across the ion position and a Gaussian-like plot is expected to emerge which corresponds to the laser intensity profile.

By making a comparison with the beam waist at the ion position one is able to obtain a plot of deflection distance against voltage. By simulating the same optical set up according to an example embodiment in 3Doptix software, a similar result was obtained.

Figure 6 shows a plot of distance moved by the laser beam at the ion position versus the voltage applied to the deflector, according to an example embodiment. As mentioned above, distance is obtained by comparing the laser beam waist to the gaussian fit obtained in Figure 5. A simulation (3Doptix) of the current optics set up according to an example embodiment was performed for different deflection angles to compare with the experimental results.

To test the feasibility of the deflector for ion addressing according to an example embodiment, the Rabi frequency of the transition when the beam is undeflected (aligned to ion) and deflected were compared. A metric typically used to quantify the quality of addressing is the cross-talk which is defined as the ratio of Rabi frequencies.

Figure 7 shows a plot of the probability of the ion in $5D_{5/2}$ state against the time of applying the 1762nm qubit transition laser (compare numeral 104 in Figure 1) when prepared in the $6S_{1/2}$ state. The same experiment was performed when the 1762nm beam is deflected and undeflected and the results were superimposed in the same plot in Figure 7. The oscillation of the probability between the two states is the Rabi oscillation and the Rabi frequency (frequency of Rabi oscillation) is extracted by performing a sinusoidal fit to this oscillation. After fitting, Rabi frequencies of 42.01 ± 0.01 kHz and 3.469 ± 0.001 kHz were obtained for the deflected and undeflected cases, respectively.

From the result, the cross-talk, herein defined as the ratio of Rabi frequencies for the undeflected to the deflected case, obtained is 8.2% (i.e. after deflection) with an estimated beam diameter of $\sim 180\mu\text{m}$. The current limiting factor in the addressability in the current optical set-up in which the example embodiment is implemented, is the position of the final focusing lens at 100mm. In the future generation traps where the device according to example embodiments will be implemented, the focal length of the lens used will preferably be reduced which will reduce the achievable beam size diameter to e.g. $9.7\mu\text{m}$. The projected cross-talk for such a system according to an example embodiment with an inter-ion spacing of about $14\mu\text{m}$ will be at 0.022%. Assuming one wants a cross talk level of $< 3.5 \times 10^{-6}$, one would only require a $20\mu\text{m}$ inter-ion spacing and given the full addressing capability of the deflector, one is able to address up to ~ 66 ions, each with the level of cross talk of $< 3.5 \times 10^{-6}$, according to an example embodiment.

In the following, the beam deflection repeatability of the deflector according to an example embodiment for addressing is investigated. To quantify repeatability, the Ramsey sequence was applied where the laser beam is deflected away during the wait time between two $\pi/2$ pulses and compared to a typical Ramsey sequence where the laser is switched off during the wait time without any deflection. If the beam comes back to the same spot after deflection, one should observe the same D-state probability as when it was undeflected and instead switched off during the wait time.

Figure 8 shows repeated measurements of a Ramsey sequence for deflected beam case, according to an example embodiment, versus undeflected beam case. For the deflected case (data 700), the laser beam is kept on during the Ramsey wait time but deflected away from the ion. For the undeflected case (data 702), the laser beam is off during the Ramsey wait time but not deflected. Here, the D-state probability obtained for the undeflected case and the deflected case is 0.94 ± 0.02 and 0.93 ± 0.03 respectively.

From the result above, one can see that since there is no observable difference between the deflected (i.e. moving laser away but remain on) and undeflected (i.e. laser on/off) case, the beam does return to the same spot after it was deflected in the deflected case, according to an example embodiment.

For some specific phase dependent operations, a precise phase control of the qubit is required. Therefore, in order to demonstrate that the deflector according to an example embodiment is capable of running such operations as well, the phase gain/loss to the ion was investigated by performing a deflection instead of switching off the laser. The experimental sequence is as follows: First, the ion is initialized in the superposition state. Next, the laser beam is deflected while keeping the laser on. Finally, the ion state is projected into the quantization axis (z in this case). For the x and y axis, an additional rotation gate R_x/R_y is applied before performing the projection.

Figures 9A-C shows the tomography of the qubit state in the three orthogonal axes x, y and z, respectively, of a Bloch sphere. In each axis, the D-state probability after projection is

determined and the cases when the beam is deflected and when the laser beam is off are compared.

From the result, one can see that there is very little difference in the z and y axis between switching off the laser and performing the deflection according to an example embodiment.

5 There is a small change in the y axis which can be quantified and mitigated in other relevant phase operations.

As described above, an example embodiment of the present invention can achieve large deviations up to 100μm using only relatively low voltages up to 25V in preliminary experiments with a prototype according to an example embodiment.

10 It is noted that while the prototype according to an example embodiment described herein uses KTN, other materials can be used in different example embodiments, including Lead Lanthanum Zirconium Titanate (PLZT, $K=3.7 \times 10^{-4} \text{ pm}^2/\text{V}^2$ to $21 \times 10^{-4} \text{ pm}^2/\text{V}^2$ depending on the crystal orientation[7]), or $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$ (BST $K \approx 3.4 \times 10^{-5} \text{ pm}^2/\text{V}^2$ [9,10]), or KTaO_3 ($K=6.0 \times 10^{-5} \text{ pm}^2/\text{V}^2$ [11]) or $\text{Bi}_{0.5}(\text{K}_{0.33}\text{Na}_{0.67})_{0.5}\text{TiO}_3$ (33BKNT, $K=1.6 \times 10^{-4} \text{ pm}^2/\text{V}^2$ [8]) or ionic liquid crystals.

Embodiments of the present invention can have one or more of the following features and associated advantages:

- Uses quadratic electro-optic effect (Kerr effect)

20 In the specific experimental test setup according to an example embodiment, the beam displacement (d), or deflection distance, shown in Figure 6 is linearly dependent on the deflection angle (θ) given by:

$$d = (a + b - \frac{ab}{f_3}) \frac{f_1 \theta}{f_2} \quad (5).$$

25 where (a+b) is the distance between lens 118 and lens 124 and f_1, f_2, f_3 are the focal lengths of lens 116, 118 and 124 respectively (Figure 1).

30 Since the beam displacement shown in Figure 6 at the ion position has a linear dependence on the deflection angle, one can directly use the deflection angle as a metric for comparison. The maximum deflection angle achievable for KEODs according to an example embodiment is ~500mrad while the typical maximum deflection angle achievable for PEODs is ~5mrad. This means that the number of qubits in a linear register that can be addressed is over 2 orders of magnitude larger for KEODs according to an example embodiment by comparing solely the maximum deflection angle achievable. In addition, this was achieved with a device footprint 2 orders of magnitude lower in a prototype according to an example embodiment. This is possible due to the quadratic dependence of the refractive index change on the applied electric field. In addition, Curie-Weiss is employed in an example embodiment to increase the permittivity by controlling the crystal temperature, noting that the Kerr effect depends on permittivity squared.

- Applied voltage for a fixed deflection angle is DC

Unlike in AODs that require AC voltages for a fixed deflection angle, there is no electrical cross-talk between multiple channels of KEOD during fixed deflection angle operation, since a DC voltage is applied.

5 - Multiplexing via single channel

Since the qubits can be addressed by deflection from a single channel, the gate information is multiplexed to multiple qubit lines. In AODs it is important to use multi-channel thereby requiring optical power splitters prior to multiple AODs. The size and low deflection angle of PEODs makes it impractical for multi-channel operations. MMDs can do multiplexing but
10 generally at a slow speed as it depends on the mechanical movement of mirror as compared to electrical switching.

- Deflection angle tuning is independent of light wavelength changes

Since KEODs according to example embodiment work using the electro-optic effect, tuning the deflection angle will not alter the frequency of the light. Since the frequency of the light
15 required for qubit transition is typically fixed, the KEODs can be directly implemented onto existing infrastructures without making any major modifications to the infrastructure. The same cannot be said for AODs which work using the acousto-optic effect. Tuning the deflection angle in this case requires an input electrical signal that is converted into sound waves in the crystal. Light that passes through the crystal undergo Bragg diffraction which deflects the
20 beam. The deflection angle is then tuned by changing the frequency of the sound waves in the crystal. However, the frequency of the deflected light is also shifted by the sound frequency. In this case, one cannot maintain the same frequency of light while changing the deflection angle which is non ideal.

It is noted that, if the capacitance is normalized to the deflection angle (nF/radian), KEODs
25 according to example embodiments are orders of magnitude faster for the same electrical drive power compared to both PEOD or MMD.

Figure 11 shows a schematic drawing illustrating a system 1100 for spatial addressing of individual atomic qubit according to an example embodiment, comprising one or more optical
30 elements 1102 for focusing a laser beam 1104 onto individual ions localized in an ion trap; and a Kerr electro-optic deflector 1108 for deflecting the focused laser beam 1104 relative to the individual ions; and a drive circuit 1110 to drive the Kerr electro-optic deflector 1108; wherein the Kerr electro-optic deflector 1108 is configured to deflect the focused laser beam 1104 using voltage pulses applied by the drive circuit 1110 to an electro-optic material 1112 of the Kerr
35 electro-optic deflector 1108 for Kerr effect led variation of the refractive index of the electro-optic material 1112.

The voltage pulses may comprise a DC component and a waveform component, wherein the DC component is chosen such that the variation of the refractive index of the electro-optic material 1112 is Kerr effect led.

The voltage pulses may comprise of transistor-transistor logic, TTL, pulses.

- 5 The voltage pulses may comprise substantially square pulses.

The voltage pulses may comprise aperiodic pulses.

The system may comprise a temperature control element 1114 for tuning the temperature of the electro-optic material 1112 for increasing the Kerr coefficient of the electro-optic material 1112 during operation.

- 10 The electro-optic material 1112 may comprise one of a group consisting of Potassium Tantalate-Niobate, Lead Lanthanum Zirconium Titanate, $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$, KTaO_3 , $\text{Bi}_{0.5}(\text{K}_{0.33}\text{Na}_{0.67})_{0.5}\text{TiO}_3$, or ionic liquid crystals.

The electro-optic material 1112 may be in crystal form.

- 15 A deflection distance of the focused laser beam 1104 may span across a plurality of the individual ions for multiplexing using a single addressing channel.

Figure 12 shows a flow-chart 1200 illustrating a method for spatial addressing of individual atomic qubit, according to an example embodiment. At step 1202, a laser beam is focused onto individual ions localized in an ion trap. At step 1204, the focused laser beam is deflected relative to the individual ions using a Kerr electro-optic deflector, wherein the deflecting of the focused laser beam comprises using voltage pulses applied to an electro-optic material of the Kerr electro-optic deflector for Kerr effect led variation of the refractive index of the electro optic material.

- 20 The voltage pulses may comprise a DC component and a waveform component, wherein the DC component is chosen such that the variation of the refractive index of the electro-optic material is Kerr effect led.

The voltage pulses may comprise of transistor-transistor logic, TTL, pulses.

The voltage pulses may comprise substantially square pulses.

The voltage pulses may comprise aperiodic pulses.

- 30 The method may comprise tuning the temperature of the electro-optic material for increasing the Kerr coefficient of the electro-optic material during operation.

The electro-optic material may comprise one of a group consisting of Potassium Tantalate-Niobate, Lead Lanthanum Zirconium Titanate, $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$, KTaO_3 , $\text{Bi}_{0.5}(\text{K}_{0.33}\text{Na}_{0.67})_{0.5}\text{TiO}_3$, or ionic liquid crystals.

The electro-optic material may be in crystal form.

A deflection distance of the focused laser beam may span across a plurality of the individual ions for multiplexing using a single addressing channel.

5 Industrial application of example embodiments

Quantum computing is a nascent technology, currently under development in corporate, start-ups and also in government institutions. The ion trap-based quantum computers face the following technical problems which example embodiments of the present invention can be able to solve:

- 10 1. Practical application of ion trap-based quantum computer: One of the current limitations in achieving high fidelity gates via beam deflection is qubit addressability error. With the current projected cross talk error of $< 3.5 \times 10^{-6}$ based on the preliminary tests performed, this can be mitigated well using example embodiments of the present invention.
- 15 2. Scalability: The currently existing technologies make it difficult to scale the systems. In the case of multiple AODs, in order to keep the same laser power per qubit the same, the total laser power required would scale linearly with the number of qubits. In a KEOD according to an example embodiment, the same laser power is deflected and can be used to address all the different qubits up to the current projected maximum number of 66 qubits. There is no scaling in terms of laser power in this case. In the case of PEODs, since the deflection angle is 2 orders
- 20 of magnitude smaller, a larger number of PEODs is required to achieve the same addressing capability as a KEOD according to an example embodiment.

Aspects of the systems and methods described herein such as the deflector drive according to example embodiment may be implemented on computing device(s), including cloud-based

25 computing device(s) and/or Internet-of-Things computing device(s), for example as functionality programmed into any of a variety of circuitry, including programmable logic devices (PLDs), such as field programmable gate arrays (FPGAs), programmable array logic (PAL) devices, electrically programmable logic and memory devices and standard cell-based devices, as well as application specific integrated circuits (ASICs). Some other possibilities for

30 implementing aspects of the system include: microcontrollers with memory (such as electronically erasable programmable read only memory (EEPROM)), embedded microprocessors, firmware, software, etc. Furthermore, aspects of the system may be embodied in microprocessors having software-based circuit emulation, discrete logic (sequential and combinatorial), custom devices, fuzzy (neural) logic, quantum devices, and hybrids of any of

35 the above device types. Of course, the underlying device technologies may be provided in a variety of component types, e.g., metal-oxide semiconductor field-effect transistor (MOSFET) technologies like complementary metal-oxide semiconductor (CMOS), bipolar technologies

like emitter-coupled logic (ECL), polymer technologies (e.g., silicon-conjugated polymer and metal-conjugated polymer-metal structures), mixed analog and digital, etc.

The various functions or processes disclosed herein may be described as data and/or instructions embodied in various computer-readable media, in terms of their behavioral, register transfer, logic component, transistor, layout geometries, and/or other characteristics. Computer-readable media in which such formatted data and/or instructions may be embodied include, but are not limited to, non-volatile storage media in various forms (e.g., optical, magnetic or semiconductor storage media) and carrier waves that may be used to transfer such formatted data and/or instructions through wireless, optical, or wired signaling media or any combination thereof. When received into any of a variety of circuitry (e.g. a computer), such data and/or instruction may be processed by a processing entity (e.g., one or more processors).

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive. Also, the invention includes any combination of features described for different embodiments, including in the summary section, even if the feature or combination of features is not explicitly specified in the summary section or the detailed description of the present embodiments.

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CLAIMS

1. A system for spatial addressing of individual atomic qubit comprising:
 one or more optical elements for focusing a laser beam onto individual ions localized in an ion trap;
- 5 a Kerr electro-optic deflector for deflecting the focused laser beam relative to the individual ions; and
 a drive circuit to drive the Kerr electro-optic deflector;
 wherein the Kerr electro-optic deflector is configured to deflect the focused laser beam using voltage pulses applied by the drive circuit to an electro-optic material of the Kerr electro-optic deflector for Kerr effect led variation of the refractive index of the electro-optic material.
- 10 2. The system of claim 1, wherein the voltage pulses comprise a DC component and a waveform component, wherein the DC component is chosen such that the variation of the refractive index of the electro-optic material is Kerr effect led.
3. The system of claims 1 or 2, wherein the voltage pulses comprise of transistor-transistor logic, TTL, pulses.
- 15 4. The system of any one of the preceding claims, wherein the voltage pulses comprise substantially square pulses.
5. The system of any one of the preceding claims, wherein the voltage pulses comprise aperiodic pulses.
- 20 6. The system of any one of the preceding claims, comprising a temperature control element for tuning the temperature of the electro-optic material for increasing the Kerr coefficient of the electro-optic material during operation.
7. The system of any one of the preceding claims, wherein the electro-optic material comprises one of a group consisting of Potassium Tantalate-Niobate, Lead Lanthanum Zirconium Titanate, $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$, KTaO_3 , $\text{Bi}_{0.5}(\text{K}_{0.33}\text{Na}_{0.67})_{0.5}\text{TiO}_3$, or ionic liquid crystals
- 25 8. The system of any one of the preceding claims, wherein the electro-optic material is in crystal form.
9. The system of any one of the preceding claims, wherein a deflection distance of the focused laser beam spans across a plurality of the individual ions for multiplexing using a single addressing channel.
- 30 10. A method for spatial addressing of individual atomic qubit comprising the steps of:
 focusing a laser beam onto individual ions localized in an ion trap; and

deflecting the focused laser beam relative to the individual ions using a Kerr electro-optic deflector,

wherein the deflecting of the focused laser beam comprises using voltage pulses applied to an electro-optic material of the Kerr electro-optic deflector for Kerr effect led variation of the refractive index of the electro-optic material.

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11. The method of claim 10, wherein the voltage pulses comprise a DC component and a waveform component, wherein the DC component is chosen such that the variation of the refractive index of the electro-optic material is Kerr effect led.

12. The method of claims 10 or 11, wherein the voltage pulses comprise of transistor-transistor logic, TTL, pulses.

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13. The method of any one of claims 10 to 12, wherein the voltage pulses comprise substantially square pulses.

14. The method of any one of claims 10 to 13, wherein the voltage pulses comprise aperiodic pulses.

15. The method of any one of claims 10 to 14, comprising tuning the temperature of the electro-optic material for increasing the Kerr coefficient of the electro-optic material during operation.

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16. The method of any one of claims 10 to 15, wherein the electro-optic material comprises one of a group consisting of Potassium Tantalate-Niobate, Lead Lanthanum Zirconium Titanate, $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$, KTaO_3 , $\text{Bi}_{0.5}(\text{K}_{0.33}\text{Na}_{0.67})_{0.5}\text{TiO}_3$, or ionic liquid crystals

17. The method of any one of claims 10 to 16, wherein the electro-optic material is in crystal form.

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18. The method of any one of claims 1 to 17, wherein a deflection distance of the focused laser beam spans across a plurality of the individual ions for multiplexing using a single addressing channel.

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