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Quantum computers based on rare-earth compounds and PT- and anti-PT symmetric qubits- Faculty Research Symposium 2022

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Quantum computers based on rare-earth compounds and PT- and anti-PT symmetric qubits

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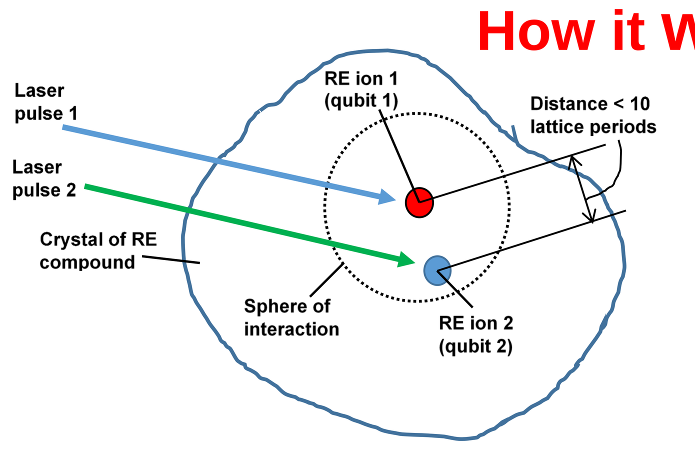
INTRODUCTION

The hardware of current quantum computing (QC) platforms is based on superconductors and ion traps. It is cumbersome and complex, requires ultra-low cryogenic temperatures and high vacuum.
Possible alternative is based on the compounds doped with the ions of Rare Earth (RE) elements. Such hardware does not need high-vacuum, can work at non-cryogenic temperatures and be less sophisticated.
The qubits in these systems correspond to the quantum levels of ^4f electrons of RE ions, and they have optical frequencies. Qubit formation is supported by the properties of RE ions: (a) weak interaction with the environment, (b) strong inhomogeneous crystal field, and (c) the ability of neighboring ions, being in some ^4f states, to interact with each other through the mechanism of Stark blockade.
Stark blockade can be used for quantum CNOT gate operations.
Anti-parity-time-symmetry (APTS) can potentially increase the decoherence time of the qubits via coupling to an APTS laser cavity.

FAST RE-BASED QUANTUM COMPUTER CONCEPT

It has been established more than a decade ago that the systems using the hyper-fine energy levels of RE-ions can meet the known DiVincenzo's criteria of quantum computers. The problems of such QCs were slow operation (no less than ~ 100 μs per operation) and the required ultra-low temperatures (~ 1 K or less). The concept of much faster QCs (< 1 ns per operation) is based on small crystals of RE-doped compounds, such as $NaYF_4$: X^{3+} (X stands for Tm, Er, etc.), which use optical frequencies for quantum computing. The qubits in these systems correspond to the quantum levels of ^4f electrons of RE ions. The validity of such QCs follows from three main properties of RE ions: (a) weak interaction with the environment (resulting in narrow homogeneous, zero phonon level (ZPL) broadening), (b) strong inhomogeneous crystal field (resulting in wide inhomogeneous spectral broadening), and (c) the ability of neighboring ions, being in some ^4f states, to interact with each other through the mechanism of Stark blockade[2] required for quantum conditional gate operations, such as Controlled NOT (C-NOT or CNOT).

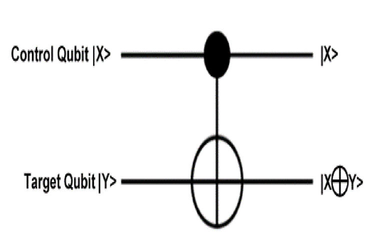
How it works

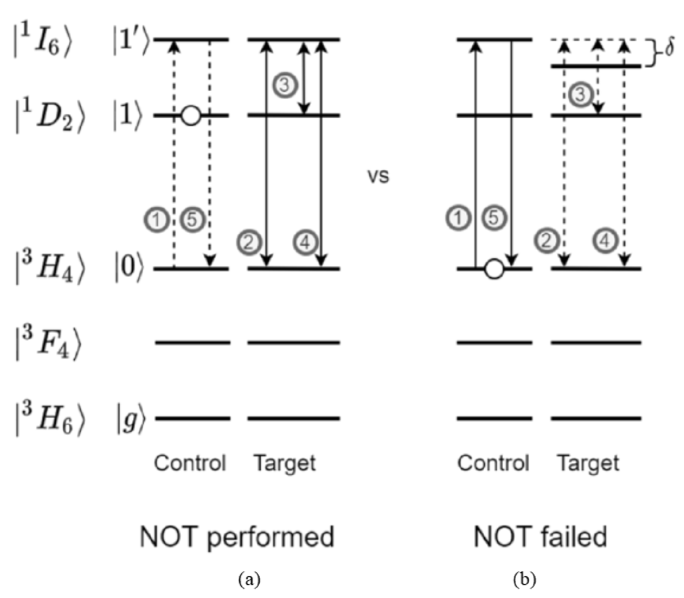


Two qubits can be created with RE ions occupying ^4f levels and interacting via the Stark blockade effect. The change of the qubit states is executed with laser pulses.

Main energy levels and CNOT gate operation scheme for Tm^{3+} in the case when the upper state $|^1I_{1/6}\rangle$ works as auxiliary state |1'⟩.

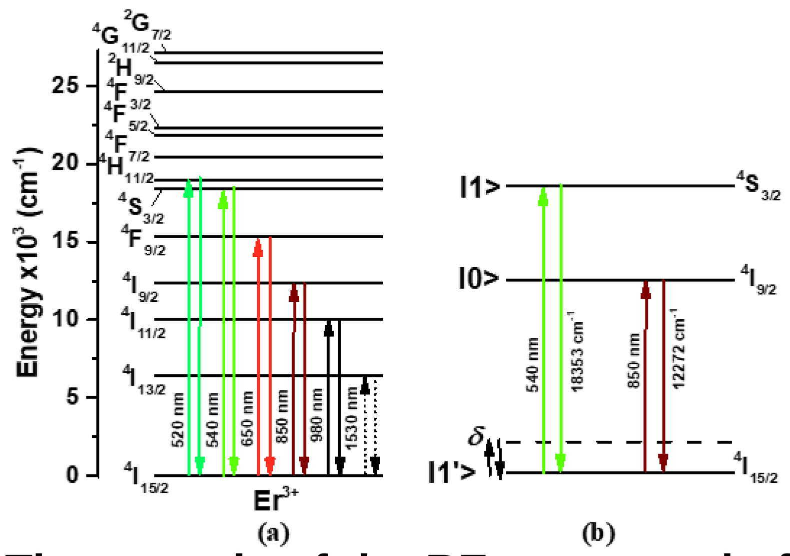
Before		After	
Control	Target	Control	Target
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	0





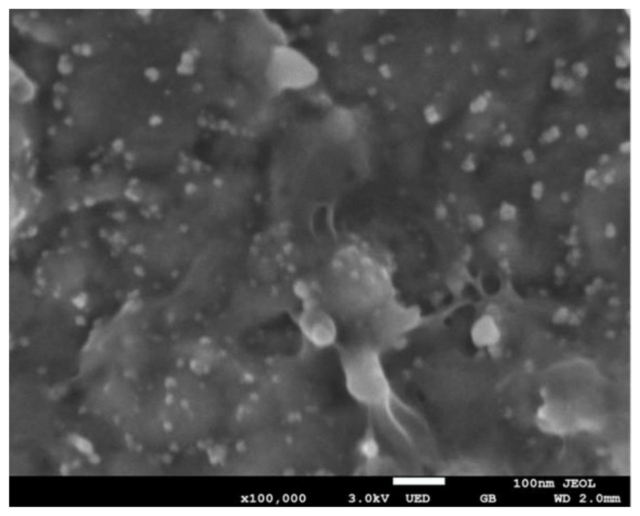
MATERIALS & DESIGN

Besides Tm^{3+}, ion of Er^{3+} in hexagonal beta-phase fluoride $NaYF_4$ is also a good candidate for fast optical QC. In the energy level diagram of Er^{3+} ground level ($|^4I_{15/2}\rangle$) can be used as an auxiliary level |1'⟩ while levels ($|^4I_{9/2}\rangle$) and ($|^4S_{3/2}\rangle$) will be qubit levels |0⟩ and |1⟩, respectively.



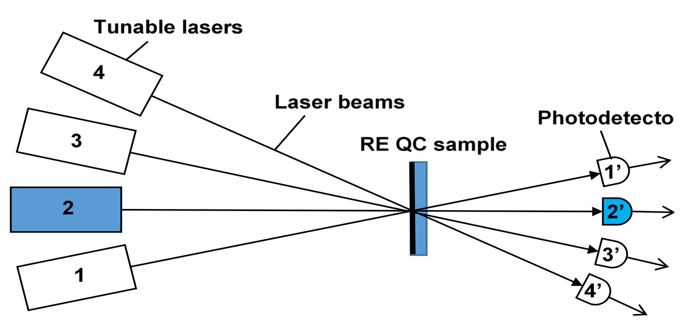
(a) Energy level diagram of Er^{3+}. (b) Possible energy levels of Er^{3+} for using in qubit.

The crystals of the RE compound of the QC can be packed in a polymer host using various methods. We have used the concurrent multi-beam multi-target pulsed laser deposition of the RE phosphor and matrix-assisted pulsed laser evaporation of the polymer (CMBMT-PLD/MAPLE).



High-resolution scanning electron-microscope (SEM) image of the polymer nanocomposite coating of PMMA+NaYF4:Yb^{3+}, Tm^{3+}. The (white spots) vary in size from 20 to 70 nm that might include from ~ 50 to 180 ion qubits.

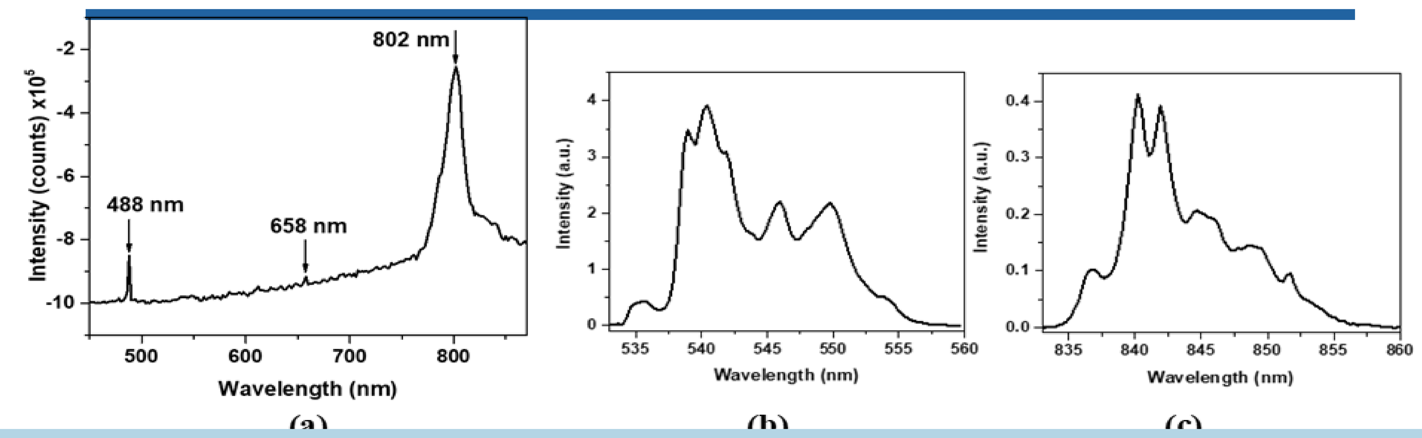
Hypothetical experimental setup consists of a battery of pulsed tunable lasers, laser beam modulators, and photodetectors for the execution of qubit manipulating pulses 1 through 5 plus two additional pulses bringing the ion of Tm^{3+} from ground state |g⟩ ($|^3H_6\rangle$) to state |0⟩ ($|^3H_4\rangle$) and between states |0⟩ ($|^3H_6\rangle$) and |1⟩ ($|^1D_2\rangle$) (blocks 4 and 4'). The wavelengths of all the lasers are realistic: from near UV (451 nm) to near IR (1459 nm). They can be easily attained with available tunable dye lasers. The status of the qubit (its current state) will be monitored by the optical spectroscopy indicating depopulation or population of the energy levels of Tm^{3+} corresponding to a particular state. The lifetime of auxiliary state |1'⟩ ($|^1I_6\rangle$) is ~ 100 μs; the lifetime of all other states is no less than 10 μs. This lifetime is basically the time of decoherence of the qubits. So, with a pulse duration of ~ 1ns, quantum logic operations can be performed at the temperature higher than the cryogenic before the qubit coherence will be lost.



Experimental setup consists of a battery of pulsed tunable lasers and photodetectors for the execution of qubit manipulating pulses

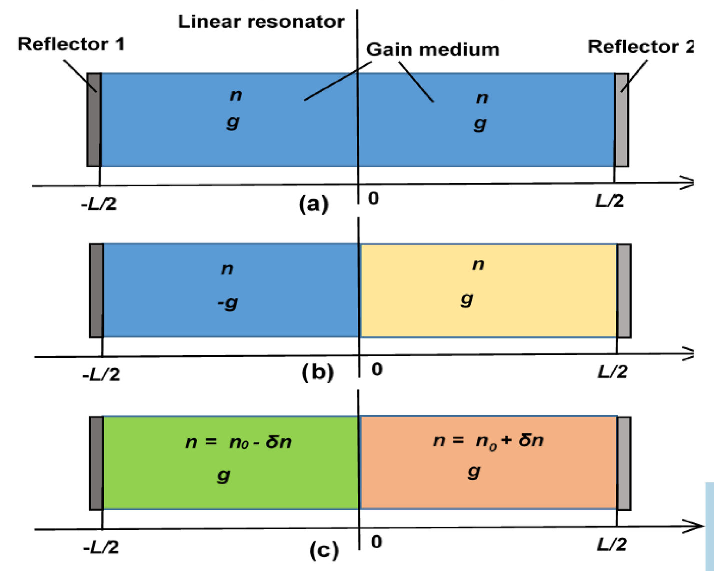
The nanocrystals of the RE compound vary in size from 20 to 70 nm that might include from ~ 50 to 180 ion qubits. Spectroscopic studies of the quantum effects in RE materials leading to the QC applications, such as up- and down-conversion, have been conducted (still at room temperature). The spectrum of the upconversion emission of the film made of polymer PMMA containing nanocrystals of $NaYF_4$:Yb^{3+}, Tm^{3+}pumped with a 980-nm laser diode is shown next.

RESULTS

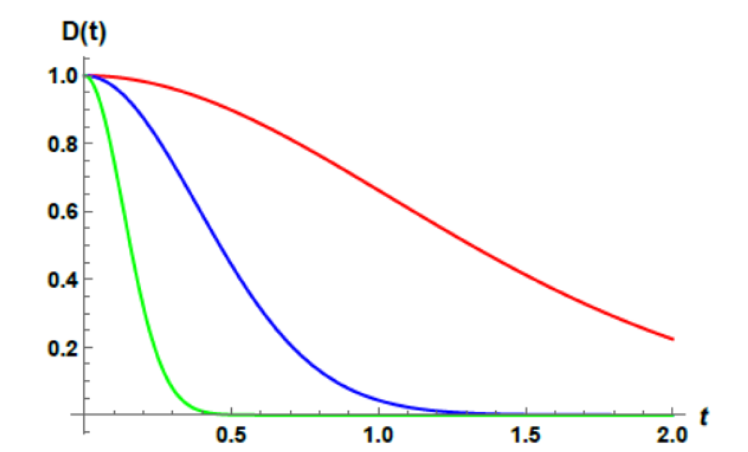


(a) Optical upconversion spectrum of the film made of PMMA and $NaYF_4$: Yb^{3+}, Tm^{3+} (980-nm pump). (b) and (c) Down-shifting spectra of $NaYF_4$: Yb^{3+}, Er^{3+} corresponding to transition ($|^4S_{3/2}\rangle$) (state |1⟩) to ($|^4I_{15/2}\rangle$) (auxiliary state |1'⟩ and ($|^4I_{9/2}\rangle$) (state |0⟩) to ($|^4I_{15/2}\rangle$) (auxiliary state |1'⟩.

PT-SYMMETRIC AND ANTI-PT-SYMMTERIC QUBITS



Schematic diagram of (a) conventional (Hermitian); (b) PT-symmetric; and (b) anti-PT-symmetric linear laser resonator.



Temporal plot of the decoherence function of a hypothetical Hermitian (1), PT-symmetric (2), and anti-PT-symmetric qubit [Cen, J. and Saxena, A., "Anti-PT-symmetric qubit: decoherence and entanglement entropy," arXiv preprint arXiv:2008.04514 [quant-ph] 11 August 2020].

CONCLUSIONS

Micro-/nanocrystals of the compounds doped with RE ions can serve as possible platforms for fast optical QCs. The qubits in these systems correspond to the quantum levels of the ^4f electrons of RE ions, and they have optical frequencies.
Such a possibility follows from three main properties of RE ions: weak interaction with the environment; strong inhomogeneous crystal field; and the existence of many ^4f states with vastly different oscillator strengths of ^4f - ^4f transitions.
Most important for the considered fast optical QCs is the ability to simultaneously find both weak and strong interacting two-level systems using these states. For QCs, ^4f states with weak interaction can be used as qubit levels. In contrast, ^4f states with strong interaction can be used as auxiliary levels to implement CNOT and other control gate operations using the Stark blockade.
The considered qubits can potentially have Hamiltonian symmetry changes to anti-PT via coupling to anti-PT-symmetric cavities based on gain media also using RE-doped compounds. That can potentially increase the decoherence time of the qubits.

ACKNOWLEDGEMENTS

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