MSc projects

Quantum memories with decoy states

A quantum memory (QM) is a device that can store an input quantum state, e.g. encoded in a light pulse, using a material with a long coherence time and then retrieve it again. A QM is an essential component in a future long distance quantum communication network, and in the Lund quantum information group we have successfully demonstrated a QM based on rare-earth ions that can reach high efficiencies. In order for the quantum communication to be theoretically secure, light pulses with only single photons have to be used. They can either be in pure single photon states, but this requires a special source which is typically not well suited for our type of QM's, or one can modulate few-photon coherent states according to a special protocol called *decoy states*. So far we have not made use of these special protocols for our research, but an interested Master's student could make this as a project. The task would be to i) learn the theory of quantum memories and decoy states, ii) program such a decoy state protocol on our setup for QM's in rare-earth ions, and iii) perform an experiment where light pulses are stored and retrieved according to this protocol.

Characterization of a new rare-earth material for quantum computing

Long lived rare-earth ions embedded in special solids are being investigated here in Lund as a potential candidate for quantum computers, and quantum photonics applications. Previously only ensembles of many ions have been used, but these are difficult to scale up to larger systems. In order to achieve that, the capability to detect and interact with single ions inside the crystal needs to be accomplished. A promising system to do that is a micrometer-sized optical cavity with a nano-crystal of such rare-earth ions inside it cooled to only 2 K above absolute zero temperature. For this purpose, we will use a new material, Y_2O_3 doped with neodymium (Nd) ions, which has never been characterized at these temperatures. The task in this project is to build an experimental setup based on an existing Titanium Sapphire laser that can characterize several properties of this material, including its capacity to store quantum information. More precisely, the sought information is spectroscopy of the transitions of Nd, lifetime and coherence time of the optical levels, lifetime and coherence time of the electron spin and nuclear spin.

Benchmarking protocols for quantum gates (theoretically challenging)

In an scientific paper already in 2008, our group demonstrated the ability to perform arbitrary quantum operations on a single qubit (quantum bit) with a fidelity above 90%. However, this was measured using only a few specific operations with little statistical analysis, and may not tell the whole story. Since then, a number of mathematically superior evaluation methods have discussed and become standard procedure, including Maximum Likelihood, Bayesian Statistics, Randomized Benchmarking and the Diamond Norm. The listed methods are very general and can be applied to a great variety of cases in research and engineering situations. In this project, the task will be to go through the theory of the different methods, analyze which ones are most suited to our specific case of qubit operations, and finally implement the best method in a laboratory setting. The last task involves programming a set of tools and using them on our small (so far one qubit) quantum computer based on rare-earth ions.

Two-qubit gate operations using ensemble qubits in Pr:Y_2SiO_5

General background

The development of the quantum information research field opens a number of new opportunities in the information technology area based on the laws of quantum physics. This includes efficient data processing, safe methods for the transmission of coded messages and teleportation of information.

There is intensive worldwide work to develop hardware by which the new concepts can be demonstrated and implemented. In Lund we develop hardware for quantum computers and quantum memories based on rare-earth-ion doped inorganic crystals.

In addition of being used for quantum information tasks, the development of quantum hardware may be equally important for the general development of micro- and nano-technology. Decreasing dimensions makes it increasingly important to fully control the quantum mechanical properties of systems and materials employed and the development of quantum computer hardware is a systematic approach for learning how to control and how to develop controllable quantum systems. Thus quantum hardware development is expected to have decisive influence of the development of the micro-electronics and nano-technology areas.

A material suitable as quantum computer hardware generally should have a large number of two-level quantum systems which can act as quantum bits. There are a number of particularly important properties that these two-level systems (qubits) should fulfil.

1. They should have long coherence times and it should be possible to control them independent of each other. Control here means the ability to prepare any of these two-level systems in an arbitrary superposition state with a definite phase.
2. It should be possible for the qubits to control each other in order to carry out two-bit gate operations and logics.
3. It should be possible to read the value of the qubits.

Our approach in Lund

In our case the qubit levels are two different hyperfine states in the ground states of rare earth ions which are doped into an inorganic crystal and these hyperfine levels can have very long coherence times. During the time we have worked with these systems we have developed a laser system with sufficient frequency and phase stability to control our rare-earth-ion wave functions with the precision needed for the quantum state manipulations.

Using qubits which consists of a large number of rare earth ions which all have the same wave function (so called ensemble qubits) we have repeatedly demonstrated high fidelity single qubit operations in our system. We have also previously attempted to carry out two-qubit gate operations using ensemble qubits, but lately more focused on developing techniques for using single ions as qubits. However, we still would like to investigate the possibility to carry out two-qubit gate operations using ensemble qubits and we also think that having carried out two-qubit operations using ensemble-qubits can be helpful for carrying out single-ion qubit operations in the future. Based on our previous attempts we know/think that there are basically two areas where we need to improve our experimental set-up. We will need to, a) be better at preparing our qubits, which requires the development of better optimised optical pumping procedures, b) develop more sensitive techniques to detect our qubits. This MSc project will address these two issues and attempt to carry out a two-qubit gate operation based on ensemble qubits in Pr:Y_2SiO_5 (Pr:YSO).

Tentative project plan

1. Reading (*Quantum information, Light matter interaction, rare earth spectroscopy*)
2. Getting familiar with the experimental set-up
3. Theoretical and/or experimental analysis of qubit detection using fluorescence
4. Theoretical analysis and/or experimental of qubit detection using frequency modulation spectroscopy or free induction decay + beating, or other (possibly related) alternatives
5. Experimental implementation of best detection method
6. Computer simulations of improved optical pumping schemes
7. Experiments on optical pumping
8. Qubit gate experiments
9. Writing report
10. Preparing oral report

Investigation of phase conjugation for medical imaging

Phase conjugation is a process where light is back-reflected in the direction where it came from as illustrated in the two figures below.

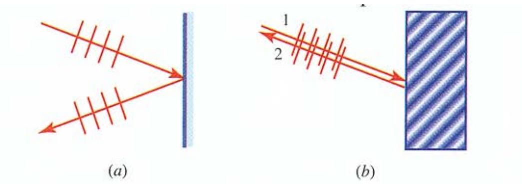


Figure 21.3-6 Reflection of a plane wave from (*a*) an ordinary mirror and (*b*) a phase conjugate mirror.

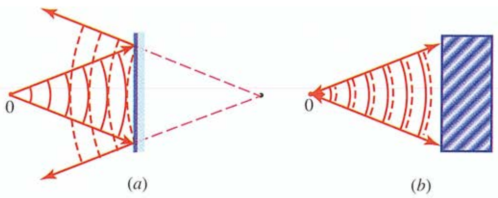
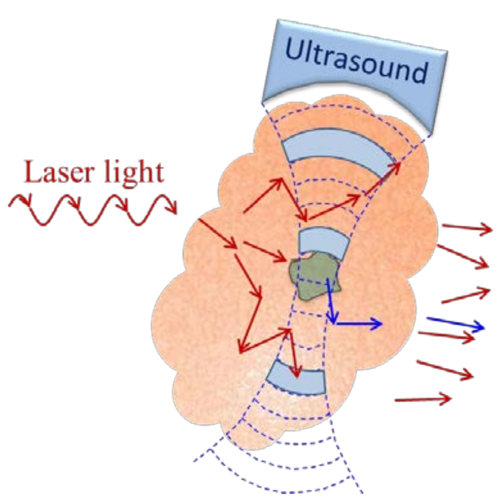


Figure 21.3-7 Reflection of a spherical wave from (*a*) an ordinary mirror and (*b*) a phase conjugate mirror.

Phase conjugation could for example be useful for focusing laser light deep inside a scattering object such as inside the body of a patient for carrying out medical treatments or diagnostics. Consider the figure below where the orange/pink area is body tissue and where we would like to focus a laser beam at some specific location, for example at the green/greyish area which could represent a tumour. If laser light is sent into the tissue it will be scattered in all directions, indicated by the red arrows in the figure. Some light will be absorbed and the rest will leave the tissue in all different directions. In the picture some of the light exiting on the opposite side to the input beam side is indicated, but a lot of light will be scattered a few times at the input side and then exit somewhere at the input side (not indicated in the figure). Ultrasound, on the other hand, is only weakly scattered in tissue and basically propagates right through the body and can be focused at any arbitrary point. Light passing through an ultrasound focus may be scattered by the ultrasound and will then also be shifted in frequency. In the figure this is indicated by changing the color of some arrows from red to blue. By checking the frequency of the light exiting it can be determined which light came from the ultrasound focus. Reflecting this light (blue arrow) by a conventional mirror will send it back into the tissue but it will be scattered in completely new direction. Using a phase conjugating mirror instead of a conventional mirror can, however, make the light retrace its previous path and go back to the ultrasound focus point. Adding a gain medium such that the "blue-arrow-intensity" is amplified before reentering the body can then result in a high intensity focused at the ultrasound focus. The present project is aimed at investigating the properties of a phase conjugating mirror created in a crystal doped with rare-earth-ions.



Tentative project plan

1. Background reading (*Properties of rare earth ion doped crystals, phase conjugation theory, light matter interaction, optical pumping in rare-earth doped crystals, medical imaging combining light and ultrasound*)
2. Learning how to use experimental equipment in the lab (*Lasers, optics, detectors, electronics, oscilloscopes, software programs for controlling the experiment, cryostat, handling of cryogenic liquids*)
3. Setting up the experiment (*Selecting components and arranging the beam path, test run without cooling the sample)*
4. Phase conjugation using resonant interactions in the crystals (*In part a repetition of previous measurements carried out earlier in the group. Cool the sample to 2K, tune the laser to a resonance and investigate the phase conjugation process. Record phase conjugation efficiency as a function of absorption, laser intensity, interaction length and laser beam angles.*)
5. Optical pumping to decrease the speed of light in the crystal (*Use previously derived pulse sequences to reconfigure the crystal absorption profile such that the speed of light in the crystal is reduced to a few tens of km/s*)
6. Investigate the phase conjugation efficiency using resonant non-interactions in but when the light in the crystal propagates very slowly. (*The light will now propagate slowly inside a non-absorbing frequency window created by optical pumping. Investigate the phase conjugation efficiency as a function of detuning from resonance, light velocity, laser intensity, interaction length and laser beam angles.*)
7. Analyse data (*In practice you will analyse data after each experiment to be able to all the time complement the measurements if needed*)
8. Write the thesis
9. Prepare and present the oral report