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Quantum Optical Control of Donor-bound Electron Spins in GaAs

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Chapter 1

Introduction

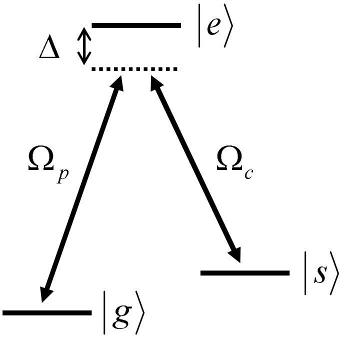

Figure 1.1: The 3-level Λ system. The two ground states $|g\rangle$ and $|s\rangle$ are optically coupled to the common excited state $|e\rangle$.

1.1 Quantum information science

Quantum information science (QIS) incorporates quantum principles into information processing and communication. The main driving force behind QIS are the ideas that quantum cryptography could enable secure communication through public channels [1], and quantum computing would efficiently solve certain computational problems that are believed to be intractable by conventional computing [2].

In the quantum information processing a bit of information is represented as a qubit, and the processing is realized by unitary quantum gates. The qubit is a single-particle state in a two-dimensional Hilbert space and can take a value of a $|0\rangle$ or a $|1\rangle$ and linear superpositions thereof. If the particle is a single photon, then the qubit can be encoded in several ways. For example, in polarization encoding, the logical zero state $|0\rangle$ can correspond to a single photon being left-circularly polarized and $|1\rangle$ to right-circularly polarized. In the case of the electron spin the $|0\rangle$ state could correspond to the spin $|\uparrow\rangle$ and the $|1\rangle$ state could be represented by the $|\downarrow\rangle$ spin.

Owing to the quantum mechanical properties of the qubit (e.g. electron spin states or optical photon states) the general qubit state can be expressed as a superposition of $|0\rangle$ and $|1\rangle$, and the general states of quantum information are superpositions of qubits.

1.2 Quantum memory

For quantum memory applications one needs to store the information carried by a qubit and to release it on demand. Photon states are often the preferred qubits for secure quantum communication because photons travel with the speed of light (and these are often referred to as the flying qubits), and because photons typically interact very weakly with the environment. In order to further utilize the information stored in quantum states of the photons, these states have to be stored in a quantum memory, where they can be processed and released afterwards as a new (or even the same) photonic quantum state. This sets two important criteria for a medium that is applicable for quantum memory.

First, quantum memory media need to have a long coherence time, as the states need to be stored long enough to perform the processing tasks at hand such as quantum gate operations.

Second, the media that are most suitable for quantum memory applications need to provide strong interactions with photons, for instance, a medium with high optical density or a medium inside a high finesse optical cavity. This criterion is needed if one needs to store the photon states effectively. The use of optical cavities is technically very demanding [3–5] therefore the search for optically dense media with good quantum coherence is of importance for developing successful QIS applications.

1.3 Electromagnetically Induced Transparency

One of the ways to incorporate quantum memory performance is to use a system where the phenomena related to Electromagnetically Induced Transparency (EIT) are possible [6]. EIT is a nonlinear optical effect that is observed in atoms with an energy-level structure resembling the letter Λ (Fig. 1.1). Two optical fields couple the excited level $|e\rangle$ to the respective ground state levels $|g\rangle$ and $|s\rangle$: the weak signal field Ω_p which may carry the quantum information and the strong control field Ω_c which is used to steer the atomic system. If the control field is absent, the signal field, which interacts with the resonant two-level system, undergoes partial or complete absorption as represented by the dashed line in the Fig.1.2(a). In the presence of the control field, the absorption of the signal is greatly reduced whenever the frequency difference of the two optical fields is close to the energy splitting between the $|g\rangle$ and $|s\rangle$ states, providing the condition that is known as *two-photon Raman resonance* (solid line in Fig.1.2(a)).

The transparency is observed when the fields are detuned from the two-photon

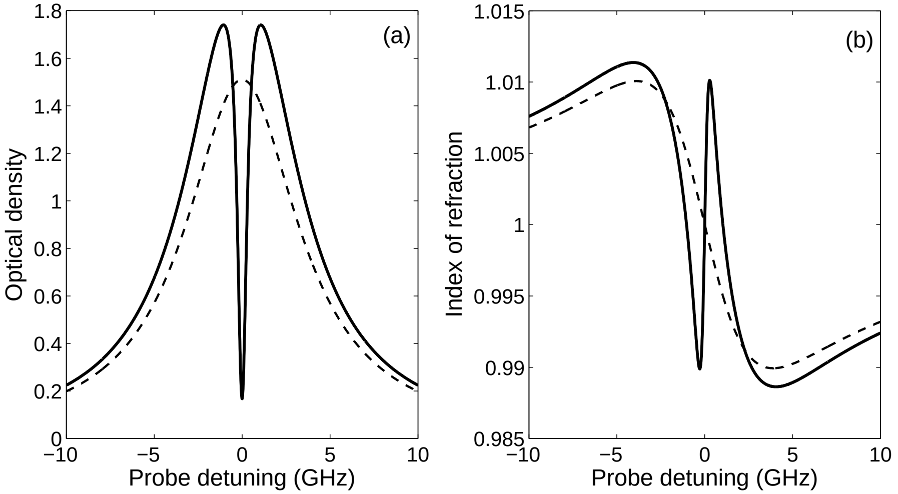

Figure 1.2: Example of optical spectra for a 10 μm long n-GaAs system with donor concentration $n_D = 10^{14}\text{cm}^{-3}$ and other parameters as in Chapter 6. (a) Optical density in the absence of the control field (dashed line) and with control field on (solid line). (b) Refractive index of the system with control field off (dashed line) and on (solid line).

resonance by no more than [6]:

$$\Delta_{EIT} \sim \frac{4}{\sqrt{\alpha L}} \frac{\Omega_c^2}{\gamma_{inh}} \tag{1.1}$$

where α is the absorbtion coefficient of the medium, L is the length of the medium, Ω_c is the Rabi frequency of the control field, and γ_{inh} is the inhomogeneous broadening of the optical transitions. The width of the EIT window is thus proportional to the intensity of the control field and can be much narrower than γ_{inh}. EIT is largely insensitive to the detuning Δ of the optical fields from their respective individual transitions. It can thus exist in the presence of inhomogeneous broadening for the optical transitions, as long as both optical transitions experience the same frequency shift.

Electromagnetically induced transparency was first observed in a vapor of Sr^+ ions [7]. Later work includes extensive studies with ensembles of alkali atoms [6], and work with a single atom in an optical cavity [3]. Observations of EIT (and the related effect of Coherent Population Trapping (CPT)) with solid state systems include an experiment with a single hole spin in GaAs quantum dot [8], rare-earth doped crystals [9, 10] and the observation of CPT with donor-bound electron spins in GaAs [11], electron spins in GaAs quantum dots [12], and NV-centers in diamond [13].

1.4 EIT in an optically dense solid state medium

The quest for observing EIT in an optically dense solid state medium is mainly driven by the use of EIT media as a quantum memory. This is based on the fact that according to the Kramers-Kronig relations, an anomaly in the absorption spectrum always comes together with an anomaly in dispersion. A light field propagating under EIT conditions experiences a large positive dispersion (Fig. 1.2(b)), which implies a reduction of the group velocity by a factor of $n_g \sim \alpha c \gamma_{inh}/4\Omega_c^2$ with respect to the velocity of light in vacuum c [6]. The group velocity can in theory be arbitrarily reduced by lowering the intensity of the control field. Experimentally, a slowdown of the velocity of the photons by up to seven orders of magnitude has been demonstrated [14].

The effect of slow light provides a basis for the quantum memory application, which functions as follows [15, 16]: a light pulse, resonant with the EIT window, enters the EIT medium and slows down. The slowdown entails spatial compression, so the pulse, whose initial spatial extent by far exceeds L, will fit inside the medium. Once it is inside, we adiabatically reduce the control field intensity and bring the group velocity down to zero, thereby "collapsing" the EIT window and storing the pulse in the medium. When the pulse needs to be retrieved, the control field is turned back on. The pulse then resumes its propagation and leaves the EIT medium. The experimental demonstration of light storage using such an example of dynamical EIT includes storage of light in an atomic vapor [17] and in magnetically trapped sodium atoms [18].

Another application of EIT media builds on the ability to prepare quantum entanglement between an optical signal pulse and a quantum state of the medium. Work in this direction was strongly stimulated by the famous DLCZ proposal, which is a scalable scheme for long-distance quantum communication [19]. An elementary step of the DLCZ procedure consists of creating a stored collective excitation in an ensemble of Λ-type atoms. All the atoms are initially in the ground state (for the ensemble denoted as the state $|0_{atom}\rangle$). They are illuminated with a weak off-resonant optical control pulse (called the write pulse), resulting in a finite probability for Raman transfer of population from $|g\rangle$ into the metastable state $|s\rangle$ (Fig. 1.1). This is operated in the limit of very weak Raman scattering (less than one Raman photon on average). An event of this type is associated with scattering (emission) of a very weak optical Raman pulse, which is then a superposition

of the states with 0 and 1 photon, $|0_{pulse}\rangle$ and $|1_{pulse}\rangle$, and can be detected by a single photon counter. Upon the detection of a scattered photon, the quantum state of the matter system is projected onto a collective excitation with for the ensemble a total population of 1 in the state $|s\rangle$ (for the ensemble denoted as the state $|1_{atom}\rangle$). The initial emission of the optical pulse entangles the state of the optical pulse with the state of the matter system, resulting in the combined state: $|\Psi_{comb}\rangle = c_0|0_{atom}\rangle|0_{pulse}\rangle + c_1|1_{atom}\rangle|1_{pulse}\rangle$.
The use of an optically dense medium for such entanglement generation is beneficial since it will facilitate forward scattering of the Raman pulse owing to collective enhancement (gain for emission in the forward direction) [19].

The read-out of the quantum state of such collective excitations can be performed by driving the atomic ensemble with a classical field, resonant with the $|s\rangle - |e\rangle$ optical transition. This measurement will project the matter system back into the $|0_{atom}\rangle$ state, while detecting 0 or 1 Raman photon from the $|e\rangle - |g\rangle$. This effectively detects whether the ensemble was in the state $|0_{atom}\rangle$ or $|1_{atom}\rangle$, respectively. It is interesting to note, that the effect of electromagnetically induced transparency is essentially a simultaneous generation and readout of the DLCZ entangled state, since in the end it recovers an initially absorbed photon and thereby leads to an optically transparent medium.

The DLCZ scheme, which relies on a high probability for the absorption or emission of a single photon, and the slow-light based quantum-memory scheme both require an optically dense medium for efficient QIS application. We therefore focus on an experimental study of an ensemble of electron spins, that are bound at neutral donor sites in bulk GaAs. The density of the donors is such that the electronic orbits of neighboring donors do not overlap (thereby resulting in an ensemble of noninteracting electron spins). We demonstrate that the electron spin dephasing time is as long as $T_2^* = 2$ ns. This system was previously shown to be suitable for Coherent Population Trapping [11] with optical control fields. In this thesis we focus on the experimental realization and study of Electromagnetically Induced Transparency with this material system.

1.5 Outline of this thesis

In Chapter 2 of this thesis we give an in-depth overview of how electron spin ensembles in semiconductors can be used for entanglement generation through the DLCZ scheme. Chapter 3 presents the electronic structure and optical properties of the material system that is central in this work: the donor-bound electron spin in low-doped n-GaAs, and its excitations. This is our system of choice for the experimental study of EIT in a semiconductor. In Chapter 4 we introduce the theoretical framework for treating the EIT phenomenon. This relies on solving the equation of motion for a density matrix operator under strong electromagnetic driving. Chapter 5 is devoted to the description of the experimental setup, which is essentially a cryogenic fiber-based confocal microscope that allows careful control of the light polarizations, even in the presence of a strong magnetic field. In Chapter 6 an experiment that demonstrates and studies EIT with donor-bound electron spins in GaAs is presented. Finally, Chapter 7 is devoted to an experiment that aims at coherent optical control of the quantum state of the electron spin ensembles with strong ultra-fast optical pulses. We have intentionally chosen to let the contents of some chapters to overlap in order to make it readable without the need to reference to the different parts of the thesis. This mainly concerns the optical spectroscopy data that are used for identification of the optical resonances and polarization selection rules associated with them.

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