Quantum Information Interface on a Photonic Crystal Chip

1st Paul Mertin
Computational Electronics and Photonics group and CINSaT
University of Kassel
Kassel, Germany
mertin@uni-kassel.de

2nd Bernd Witzigmann
Electrical Engineering Department
Friedrich-Alexander University Erlangen-Nürnberg
Erlangen, Germany
bernd.witzigmann@fau.de

***Abstract*—Quantum systems for information processing rely on the distribution of quantum information in a network. Lanthanide complexes coupled to an optical cavity can act as an interface between a stationary and a flying QuBit. Here we show that in such a system the stationary quantum information can be mapped onto a photon, paving the way for a node in photonic quantum network.**

***Index Terms*—quantum information, cavity QED, photonic crystals**

I. Introduction

Quantum network nodes enable applications in quantum sensing, secure communication or quantum computing [1]. Such a quantum node needs to be able to translate information imprinted on a stationary QuBit to a flying QuBit to connect distant nodes. Optically addressable molecules or atoms, such as Lanthanides (Er, Yb, ...), coupled to an optical cavity appear as a promising candidate for such a node [2], [3]. There, the stationary QuBit is the stationary atom and the flying QuBit is an emitted photon. The quantum information can be encoded in different properties of the photon, such as polarization or real space. A robust method however is the time-bin encoding, which appears promising for a photonic crystal platform and was already proven feasible in a different system [4].

Here, an optical cavity in a semiconductor photonic crystal slab is used. These cavities allow for high Q- and Purcell factors (F_P). The cavity is analyzed using a Finite Element Method (FEM).

The results of the FEM are fed into a quantum mechanical simulation to study the cavity and atom population dynamics for a suitable addressing protocol.

This paper is organized as follows. First the photonic crystal cavity characteristics obtained by the FEM are briefly discussed. Second the atoms level scheme and addressing protocol is presented. Third the results are shown. At the end a conclusion is given.

II. Photonic Crystal Slab Cavity

The photonic crystal slab studied here consists of Galliumphosphide (GaP) and has a thickness of $160nm$. The target resonance wavelength is $980nm$ to match a level transition of Yb [3].

In the FEM framework the wave equation in frequency domain is solved for the eigenvalue:

$$\nabla \times \bar{\bar{\mu}}^{-1} \nabla \times \vec{E} - k^2 \bar{\bar{\epsilon}} \vec{E} = 0, \tag{1}$$

where $\vec{E}$ is the electric Field, k is the wavenumber, $\bar{\bar{\mu}}$ and $\bar{\bar{\epsilon}}$ are tensors for the permeability and permittivity, respectively [5]. The Green's function can be obtained from the results:

$$G(k) = \sum_n \frac{1}{k^2 - k_n^2} \frac{|\vec{E_n}\rangle\langle\vec{E_n}|}{\langle\vec{E_n}|\bar{\bar{\epsilon}}|\vec{E_n}\rangle}, \tag{2}$$

where n is the number of modes. As we are dealing with high Q cavities we only consider one mode. With this the important figures of merit for the cavity can be calculated: $Q = k_R/2k_I$ and $F_P = \frac{2\pi}{k} Im\{G\}$. Depending on where the atom is placed within the cavity (e.g. inside the slab or on the surface) the atom will experience different Purcell factors and coupling strengths.

The coupling can be calculated from the Green's function and a solved Jaynes-Cummings Hamiltonian:

$$|g|^2 = \frac{\omega_c |d|^2 Im\{G\}}{2Q\hbar\varepsilon_0}, \tag{3}$$

where ω_c is the resonance frequency of the cavity and $|d|$ is the transition dipole moment of the atom coupling to the cavity.

III. Stationary QuBit

The considered atom offers a hyperfine level scheme as a QuBit and an optical transition for readout, as shown in Fig.1 [3]. For the addressing protocol three subsequent electromagnetic (EM) pulses $\Omega_{1,2,3}$ are needed, where Ω_1 and Ω_3 have the same shape. The EM pulses Ω_1 and Ω_3, drive the cavity coupled transition, initiating photon emission. The QuBit is realized in the fine level splitting between level 1 and level 2 and can be flipped by an EM pulse Ω_2. The protocol is:

1) the first pulse Ω_1 transfers the population in $|1\rangle$ to $|e\rangle$, where a photon will be emitted
2) Ω_2 flips the population of $|0\rangle$ and $|1\rangle$
3) with Ω_3 the first step is repeated, this time for the initial population of $|0\rangle$

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We note that the emitted photon will be a superposition of early and late emission. A measurement will either show an early or a late photon, where the detection probability is proportional to the initial population in $|1\rangle$ or $|0\rangle$, respectively.

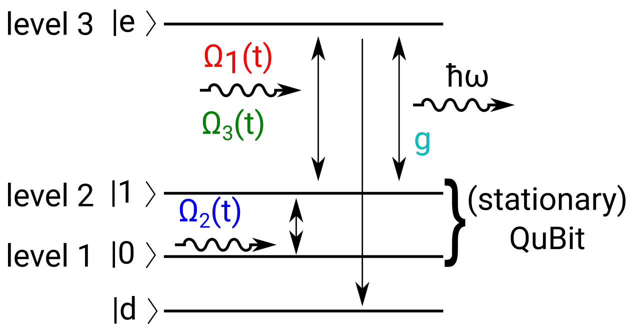

Fig. 1. Level scheme for entangling a stationary QuBit with a photon in a time bin realization.

A. Quantum Model

To analyze the interaction dynamics of the coupled system the following Hamiltonian is set up:

$$H = \Omega_1(t)|l2\rangle\langle l3| + \Omega_2(t)|l1\rangle\langle l2| + g|l3\rangle\langle l2|c^\dagger + h.c., \quad (4)$$

where $l\{1,2,3\}$ denote the levels $1,2,3$ and $c^\dagger$ is the annihilation operators for the cavity. Ω_1 and Ω_2 are the coherent EM field pulses. The emitter (or more precisely level transition dipole) coupling strength to the cavity is g, as in (3). All EM fields and the cavity are in tune with the respective level transition. It should be noted, that the coupling and EM fields shown in Fig.1 can drive the populations in both directions. Furthermore Ω_3 is the same EM pulse as Ω_1 only applied at a different time.
Decay is added as Lindblad terms with $\kappa = \frac{\pi c}{\lambda Q} = 62 \cdot 10^9 s^{-1}$ for the cavity decay and $\gamma = 1 \cdot 10^9 s^{-1}$ as the decay rate from level 3 to a dump level, which is lost from the system and not further considered.

IV. Results

To analyze the dynamics of the system we assume the QuBit to be perfectly initialized in one state (either $|0\rangle$, $|1\rangle$ or a mixture). The EM pulses Ω_1 and Ω_2 were optimized using a Nelder-Mead method for ideal population transfer (and therefore high fidelity). This results in the addressing pulse sequence shown in the upper plot of Fig.2. The cavity was designed for improved F_P to have: $Q = 16696$ and $F_P = 1331$ [6].
The population dynamics are shown in Fig.2 for an initial QuBit with $|\Psi\rangle = \sqrt{0.6}|1\rangle + \sqrt{0.4}|0\rangle$. The fidelity is defined as the population of level 1 after one pulse sequence divided by the initial population of level 2. Due to the strong coupling we see Rabi-oscillations between the cavity and the transition between level 2 and level 3. There, by applying the protocol pulse sequence the early (due to Ω_1) and late (due to Ω_3) peak photon population represents the population of the QuBit $|1\rangle$ and $|0\rangle$ state, respectively.

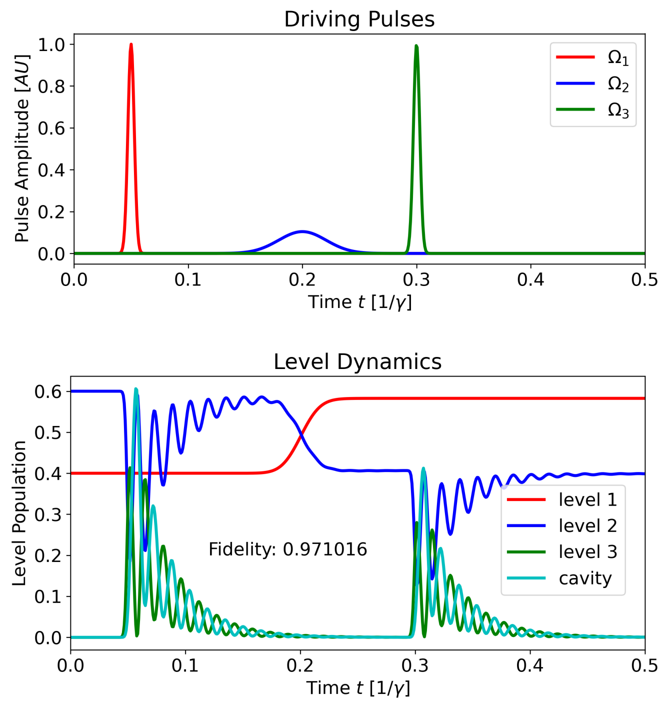

Fig. 2. Top: Pulse sequence. Ω_1 and Ω_3 drive the optical transition, Ω_2 flips the QuBit. Bottom: Population dynamics for optimized pulses for mixed QuBit starting condition.

V. Conclusion

Transferring the information stored in a QuBit, realized in the level population, to a flying QuBit, realized by arrival (or sending) times of a photon is a crucial step towards a photonic quantum network. Here we could show that by coupling a suitable atom to a semiconductor photonic crystal slab cavity and applying appropriate EM field pulses the QuBit population can be mapped onto the emitted photon time.

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