Fast Polarization Manipulation

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Research Proposal

Under the supervision of

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April 2023

Abstract

The generation of a pair of entangled photons from the biexcition-exciton cascade is complicated by the presence of fine structure splitting (FSS)[**Winik2017**] that leads to the degradation of the degree of entanglement. Many methods were implemented to overcome the problem with varying degrees of success, but the problem continues to persist.

This research proposal aims to take a different approach to the problem by implementing a scheme for the restoration of the degree of entanglement of the photon pairs by fast polarization manipulation [**Fognini18**, **Varo2022**].
This scheme can be potentially used as a method for fast photon rerouting in integrated photonics.

Contents

1 Introduction

Self-assembled quantum dots (QDs) are nano-scale semiconductor structures that can confine electrons and holes in three dimensions. Due to their small confinement length relative to the particle's wavelength, the energy levels of the QD are quantized with properties similar to atoms which lead them to be described as "Artificial Atoms" [**Kastner1993**].

1.1 Self assembled QDs

Populating the dot with electrons and holes is done with either resonant or non-resonant excitation. In resonant excitation, the absorption of a photon excites an electron from the valence band to the conduction band where the photon energy is equal to the difference in energy between these levels. The missing electron in the valence band is treated as a hole with a spin opposite in direction of the excited electron. This electron-hole pair form the bright exciton (BE) due to the Coulomb interaction between the negative electron and the positive hole. In non-resonant excitation, a strong laser excites the surrounding bulk material that generates electrons and holes in the vicinity of the QD. These charge carriers are free to move inside the semiconductor which can be randomly trapped in the quantum dot potential.

The projection of the spin of the electron on the z-axis (growth axis) of the QD can be either 1/2 or -1/2 while for the heavy hole, the spin projection is either 3/2 or -3/2 such that the two spin states of the bright exciton are $\left|\frac{1}{2}, -\frac{2}{3}\right\rangle$ and $\left|-\frac{1}{2}, \frac{2}{3}\right\rangle$ with a total spin in the z direction of ± 1. While in the case of electron-hole pair with parallel spin, the spin states are $\left|\frac{1}{2}, \frac{2}{3}\right\rangle$ and $\left|-\frac{1}{2}, -\frac{2}{3}\right\rangle$ with a total spin of ± 2. In figure 1 we describe two of the simple configurations that we can have in a QD. We start with empty dot which we denote by $|0\rangle$.

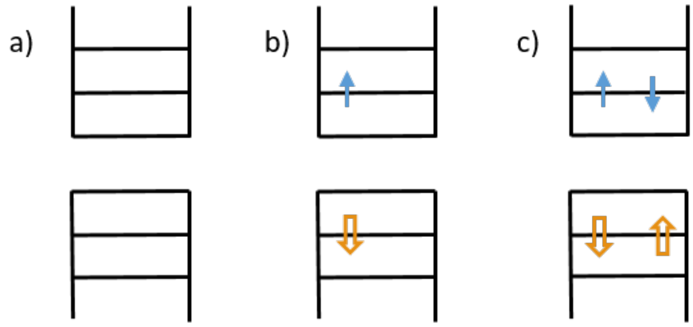


Figure 1: Schematic of the energy levels in the quantum dot for empty quantum dot (a),exciton (b) and a biexciton (c)

while having two electron-hole pairs falling in the dot a biexciton is formed and we denote it by $|XX_0\rangle$. The total energy of the biexciton differs from twice the energy of the exciton due to the interaction between all the particles.

In an ideal QD, the radiative decay path of the biexciton back to the ground state goes via one path, but due to the anisotropy of the QD, the energy of exciton is split in what is defined as the fine structure splitting (FSS) as seen in figure **??**b. Here we refer to the up (down) spin of the electron as $|\uparrow\rangle$ ($|\downarrow\rangle$ and the up (down) spin of the hole as $|\Uparrow\rangle$ ($|\Downarrow\rangle$ such as the two eigenstates of the exciton are $|\uparrow\Downarrow\rangle$ and $|\downarrow\Uparrow\rangle$,and the decay from these states result in the emission of photons with co-linear polarization. Here we refer to them as horizontal $|H\rangle$ and vertical $|V\rangle$. We can represent these two rectilinear bases using the Bloch sphere where the poles in the sphere are $|H\rangle$ and $|V\rangle$ base.

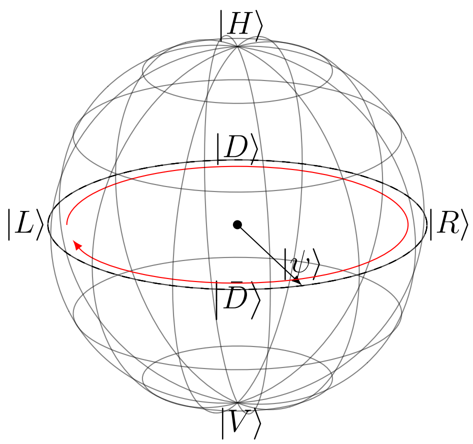
In addition to the rectilinear polarization states, We can define the diagonal linear and the circular polarization bases:

$$\begin{aligned} |L\rangle &= (|H\rangle + i\,|V\rangle)/\sqrt{2} \\ |R\rangle &= (|H\rangle - i\,|V\rangle)/\sqrt{2} \end{aligned} \tag{1}$$

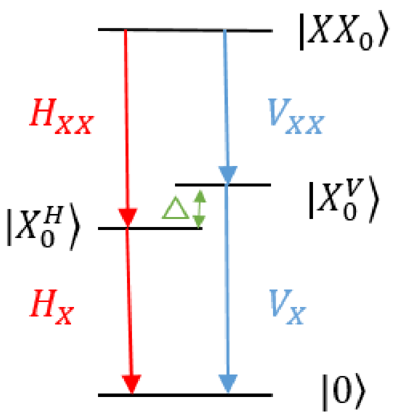
where $|R\rangle$ and $|L\rangle$ are the left and right circular bases respectively, and:

$$\begin{aligned} |D\rangle &= (|H\rangle + |V\rangle)/\sqrt{2} \\ \left|\bar{D}\right\rangle &= (|H\rangle + |V\rangle)/\sqrt{2} \end{aligned} \tag{2}$$

$|D\rangle$ and $\left|\bar{D}\right\rangle$ are the diagonal and anti-diagonal bases respectively



a)



b)

Figure 2: a) A Bloch sphere representation of the spin state. A point on the sphere represents an arbitrarily polarized spin state. b) Decay paths of the biexciton back the ground state where the red arrows represent the emission of a H polarized photon and blue arrows represent the emission of V polarized photon.

When the biexciton spontaneously radiatively decays it emits a photon leaving in the QD an exciton in coherent superposition of its two eigenstates. The optical selection rules for the biexciton radiative recombination and the lack of information by “which path” the recombination proceeds result in entanglement between the exciton state and the polarization state of the emitted photon. Their mutual wave function is given by:

$$|\psi_{X^0}\rangle = \frac{1}{\sqrt{2}}(\left|H_1 H_H^1\right\rangle + \left|V_1 V_V^1\right\rangle) \tag{3}$$

here $|H_1\rangle$ and $|V1\rangle$ are the two rectilinear polarization states of the first (biexciton) photon. since the two exciton eigenstates are not degenerate, the relative phase between these eigenstates precesses in time with a period of $T_P = h/\triangle$, where where h is the Planck constant and $\triangle$ is the exciton FSS [**rwinik2017**]. This precession is schematically described on the exciton Bloch sphere in figure. $2a$. The precession “stops” when the exciton recombines and the radiative cascade is completed with the emission of a second photon. The two photons are thus entangled. Their mutual wave function depends on the recombination time and is given by:

$$|\psi_{X^0}\rangle = \frac{1}{\sqrt{2}}(|H_1 H_1\rangle + e^{-i2\pi t/T_P}\,|V_1 V_2\rangle) \tag{4}$$

where $|H_2\rangle$ and $|V_2\rangle$ are the second (exciton) photon polarization states and $t = t_{X_0} - t_{XX_0}$ is the time between the emission of the biexciton photon t_{XX_0} and that of the exciton t_{X_0}.

2 The Research Proposal

3 Preliminary Results

Appendices

Appendix I

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Appendix 2

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