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PHOTON GENERATION EFFICIENCY AND ENTANGLEMENT IN QUANTUM DOT SYSTEMS

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Abstract: The interest in quantum dots as sources of quantum light is based upon the potential for high photon generation efficiency that originates in their atom-like energy structure. Quantum dots can be excited resonantly and coherently, where generation of photon pairs calls for a specific excitation method of two-photon resonant excitation of the biexciton. Though this method is very efficient, it was very often showing sub-unity excitation efficiency that could be observed, for instance, in the maximum amplitude of the Rabi oscillations. Investigation of the dephasing processes in this excitation technique is of strategic interest for quantum communication technologies.
Keywords: quantum dots, entanglement, quantum communication.

1. INTRODUCTION

Quantum dots are solid-state emitters of single photons. Their ability to perform this function originates in their discrete energy structure. In this respect, quantum dots very closely resemble atoms and are, therefore, very often called artificial atoms. Quantum dots can generate single photons [1] as well as pairs of single photons [2]. Here, the recombination of a single electron-hole pair trapped in the quantum dot potential yields the emission of a single photon. If the quantum dot has trapped two electron-hole pairs, they bound to form a biexciton (excitonic molecule). The recombination of the biexciton results in a photon pair that is emitted as a temporarily ordered biexciton-exciton cascade. It has been demonstrated that such cascade photons can show entanglement [3, 4].

The applications of single photons and entangled photon pairs include long distance quantum communication [5, 6], linear optical quantum computing [7], and quantum-enhanced measurement and sensing [8, 9]. Another, more traditional method to produce such states of light is spontaneous parametric down-conversion [10]. Although down-conversion-based single photon sources are well established and in a number of ways are still outperforming quantum dots, there is an intrinsic limit of their performance. Namely, they give photon pairs with thermal statistics [11]. Consequently, a high probability to generate a photon pair yields also a high probability for generation of multiple pairs [12]. On the other hand, quantum dots show sub-Poissonian statistics and very low multiphoton contribution [13]. Therefore, with further technological improvements for increased photon generation probability, quantum dots promise to form a very powerful source of single photons.

The true potential of quantum dots is, nonetheless, only used if they are driven resonantly, because only under such excitation conditions one can reach an emission probability equal to unity. Unfortunately, resonant excitation is not straightforward to achieve in quantum dots. Despite this, there have been several implementations where the quantum dot was driven resonantly, one of those pioneered by the author [2]. These experiments used specific excitation schemes and geometries, like two-photon resonant excitation of the biexciton [2] and orthogonal excitation and collection [14, 15].

2. RESONANT EXCITATION

A photon generation device employed in quantum information processing tasks must achieve a high success probability to produce a single photon. In atom-like systems, such behaviour is achievable by means of coherent population inversion. Likewise, the discrete energy structure of quantum dots makes this system suitable for driving such a process. On the other hand, despite the favorable energetic structure, it is hard to achieve resonant excitation in semiconductor embedded quantum dots. The first, and most important reason is the excess laser scattering that is hard to distinguish from

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the single photon signal emitted by the quantum dot. Therefore, the traditional way to excite quantum dots is above-band excitation. Here, one uses a laser with energy higher than any transition in the quantum dot. This laser creates a multitude of carriers in the vicinity of the quantum dot that can be probabilistically trapped in the quantum dot potential. This process is schematically illustrated in Figure 1.

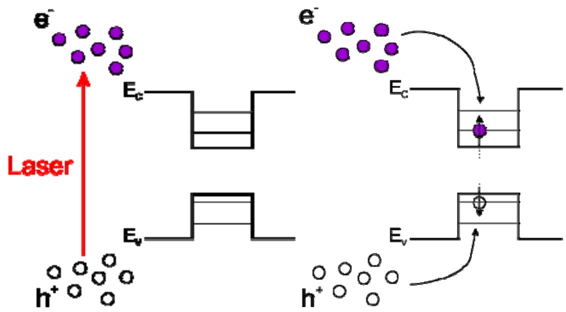

Figure 1. Schematic of the above band excitation. The laser with energy much higher than any transition in the quantum dot generates carriers in the vicinity of the quantum dot. The carriers will gradually lose energy via scattering and can be probabilistically trapped in the quantum dot potential

While it is possible to both saturate the quantum dot transitions and to achieve very high single photon count rates, the probabilistic nature of this process reduces the suitability of such a source for quantum information protocols. Another negative feature of the above-band excitation is related to how exactly the quantum dot levels are populated. Namely, biexciton photons will be created once the exciton level has been saturated and, therefore, the saturation of the biexciton level itself demands a very large number of carriers in the quantum dot vicinity. Such an experimental configuration is very unfavorable because it promotes the dephasing of the quantum dot levels due to the electric field fluctuations and causes poor photon statistics properties due to processes like carrier re-capture [16].

Two-photon resonant excitation of the biexciton [2] is an experimental implementation that simultaneously solves both problems: laser scattering and probabilistic generation of photon pairs. Here, one exploits the biexciton binding energy in order to drive the quantum dot system using a virtual resonance that is placed halfway in energy between the exciton and biexciton (see Figure 1(a)) and therefore is not resonant to any of them. The photoluminescence obtained in above-band excitation of the quantum dot is shown in Figure 1(b). There we can observe the lines of the quantum dot emission. For comparison, the emission spectrum under resonant excitation is shown in Figure 1(c.) This spectrum shows an additional line coming from the scattered excitation laser light. The physical basis of the phenomenon we exploit here, the biexciton binding energy, is the Coulomb interaction present when two electronhole pairs are trapped inside the quantum dot potential. As the first pair of carriers recombine and the biexciton photon is emitted, the energy levels in the quantum dots will change and the second photon to be emitted (exciton photon) will not have the same energy as the biexciton photon. Therefore, we always observe the exciton and biexciton emission as two energetically well separated lines.

3. THEORETICAL DESCRIPTION

To give a theoretical model of the quantum dot under two-photon resonant excitation and determine the optimum parameter regime, we use a standard Lindblad master equation

$$\dot{\rho} = i[\rho, H] + \mathcal{L}(\rho) \tag{1}$$

that is based on the effective quantum dot Hamiltionian given in the following form

$$\begin{aligned} H = &\tfrac{1}{2}\Omega(t)(|g\rangle\langle x| + |x\rangle\langle b| + h.c.) \\ &+(\delta_x - \delta_{xx})|x\rangle\langle x| - 2\delta_{xx}|b\rangle\langle b| \end{aligned} \tag{2}$$

and a Liouvillian damping operator

$$\mathcal{L} = \sum_i \mathcal{L}_i = \sum_i \frac{\gamma_i}{2}\left(2A_i^\dagger \rho A_i - A_i A_i^\dagger \rho - \rho A_i A_i^\dagger\right) \tag{3}$$

where

$$\hat{A}_1 = |b\rangle\langle x| \tag{4}$$

$$\hat{A}_2 = |x\rangle\langle g| \tag{5}$$

describe the biexciton and exciton decay, respectively. The corresponding dephasing mechanisms are

$$\hat{A}_{bb} = (|b\rangle\langle b| - |x\rangle\langle x|) \tag{6}$$

$$\hat{A}_{xx} = (|x\rangle\langle x| - |g\rangle\langle g|). \tag{7}$$

In Equation (2), the parameter δ_x is the energy difference between the virtual level of the two-photon resonance and the energy of the exciton, while δ_{xx} is the detuning between the laser energy and the two-photon resonance. The parameters we used in this phenomenological model (lifetimes, coherence lengths, etc) were determined experimentally. The energy scheme of the quantum dot is depicted in Figure 2(a).

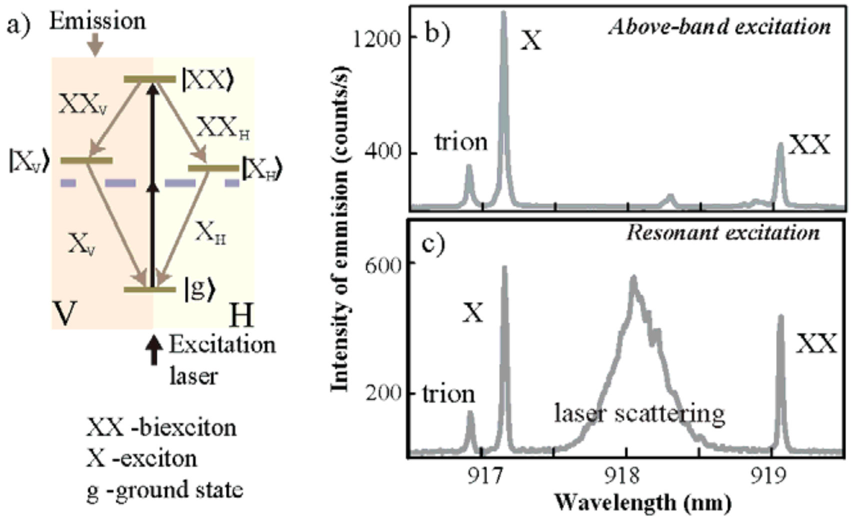

Figure 2. (a) Quantum dot energy scheme. Fine structure splitting is the energy difference between two exciton levels X_H and X_V. In the process of two-photon resonant excitation, the laser coherently couples the ground and the biexciton state via a virtual level (shown in dashed line). (b) Photo-luminescence of a quantum dot obtained in above-band excitation, (c) Emission spectrum of the same quantum dot measured under resonant excitation

4. EXPERIMENTAL RESULTS

The specific quantum dot we investigated here showed experimentally lifetimes of the exciton and the biexciton photons of 711 ps and 405 ps, respectively. The results of the field correlation function measurements for the same quantum dot were 119 ps and 211 ps for exciton and biexciton, respectively. The Figure 3, show the Rabi oscillations performed using 12 ps long excitation pulses. The observed Rabi oscillations can be explained by theory approach given in [17].

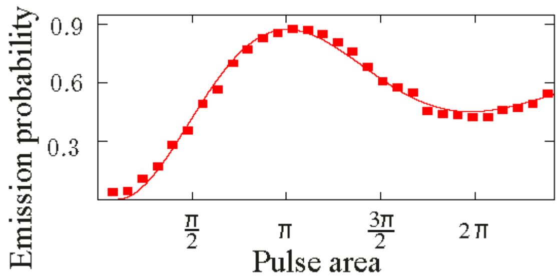

Figure 3. Emission probability for a biexciton, as a function of the laser pulse area. The error bars are smaller than symbols

4. CONCLUSION

We have investigated the problem of decoherence of excitation process in quantum dots. Our theoretical study indicates that by careful optimization of the parameters of the excitation pulse, one can minimize the decoherence and therefore reach very high photon pair emission probability. Additionally, using the same approach, we observed a very high degree of time-bin entanglement of the emitted photon pairs [17]. This is possible because a high degree of time-bin entanglement is in a direct relation with coherence of excitation process. The same theoretical study can be readily extended to other quantum dot systems, where it can be used to determine the set of optimal parameters.

5. REFERENCE

[1] P. Michler, A. Kiraz, C. Becher, W. V. Schoenfeld, P. M. Petroff, L. Zhang, E. Hu, and A. Imamoglu, *A quantum dot single-photon turnstile device*, Science, Vol. 290 (2000) 2282.

[2] H. Jayakumar, A. Predojević, T. Huber, T. Kauten, G. S. Solomon, and G. Weihs, *Deterministic photon pairs and coherent optical control of a single quantum dot*, Physical Review Letters, Vol. 110 (2013) 135505.

[3] N. Akopian, N. H. Lindner, E. Poem, Y. Berlatzky, J. Avron, D. Gershoni, B. D. Gerardot, and P. M. Petroff, *Entangled photon pairs from semiconductor quantum dots*, Physical Review Letters, Vol. 96 (2006) 130501.

[4] R. M. Stevenson, C. L. Salter, J. Nilsson, A. J. Bennett, M. B. Ward, I. Farrer, D. A. Ritchie, and A. J. Shields, *Indistinguishable entangled photons generated by a light-emitting diode*, Physical Review Letters, Vol. 108 (2012) 040503.

[5] H. J. Briegel, W. Dür, J. I. Cirac, and P. Zoller, *Quantum repeaters: the role of imperfect local operation in quantum communication*, Physical Review Letters, Vol. 81 (1998) 5932.

[6] N. Gisin, G. Ribordy, W. Tittel, and H. Zbinden, *Quantum cryptography*, Reviews of Modern Physics, Vol. 74 (2002) 145.

[7] E. Knill, R. Laflamme, and G. J. Milburn, *A scheme for efficient quantum computation with linear optics*, Nature, Vol. 409 (2001) 46.

[8] M. W. Mitchell, J. S. Lundeen, and A. M. Steinberg, *Super-resolving phase measurements with a multiphoton entangled state*, Nature, Vol. 429 (2004) 161.

[9] T. Nagata, R. Okamoto, J. L. O'Brien, K. Sasaki, and S. Takeuchi, *Beating the standard quantum limit with four-entangled photons*, Science 316, 726 (2007).

[10] P. G. Kwiat, K. Mattle, H. Weinfurter, A. Zeilinger, A. V. Sergienko, and Y. Shih, *New high-intensity source of polarization-entangled photon pairs*, Physical Review Letters, Vol. 74 (1995) 4337.

[11] D.F. Walls and G. J. Milburn, *Quantum optics*, Springer (1994).

[12] O. Kuzucu and F. N. C. Wong, *Pulsed Sagnac source of narrow-band polarization-entangled photons*, Physical Review A, Vol. 77 (2008) 032314.

[13] A. Predojević, Miroslav Ježek, T. Huber, H. Jayakumar, T. Kauten, G. S. Solomon, R. Filip, and G. Weihs, *Efficiency vs. multi-photon contribution test for quantum dots*, Optics Express 22, 4789 (2013).

[14] Muller, E. B. Flagg, P. Bianucci, X. Y. Wang, D. G. Deppe, W. Ma, J. Zhang, G. J. Salamo, M. Xiao, and C. K. Shih, *Resonance fluorescence from a coherently driven semiconductor quantum dot in a cavity*, Physical Review Letters, Vol. 99 (2007) 187402.

[15] Y. -M. He, Y. He, Y. -J. Wei, D. Wu, M. Atatüre, C. Schneider, S. Höfling, M. Kamp, C. -Y. Lu, and J. -W. Pan, *On-demand semiconductor single-photon source with near-unity indistinguishability*, Nature Nanotechnology, Vol. 8 (2013) 213–217.

[16] Peter, E. et al., *Fast radiative quantum dots: From single to multiple photon emission*, Applied Physics Letters, Vol. 90 (2007) 223118.

[17] T. Huber et al., *Coherence and degree of time-bin entanglement from quantum dots*, Phys. Rev. B., Vol 93 (2016) 201301(R).

УПОТРЕБА КВАНТНИХ ТАЧАКА ЗА КВАНТНУ КОМУНИКАЦИЈУ

Сажетак: Квантне тачке су емитери свјетлости са особинама које се могу објаснити само са становишта квантне механике. Посебно занимљива особина ових физичких система јесте њихова енергетска структура која је веома слична структури хелијумовог атома. Захваљујући управо овој особини квантне тачке емитују пулсеве свјетлости који у просјеку не садрже више од једног фотона.

Кључне ријечи: квантне тачке, квантно спрезање, квантна комуникација.