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Active Reset of an Entangled-LED for Superequilibrium Entangled Photon Generation

Jonathan R. A. Müller,[1,2] R. Mark Stevenson,[1] Joanna Skiba-Szymanska,[1] Ginny Shooter,[1,3] Jan Huwer,[2] Ian Farrer,[3,*] David A. Ritchie,[3] and Andrew J. Shields[1]

[1] Toshiba Europe Ltd., Cambridge Research Lab.,
208 Science Park, Milton Road, Cambridge CB4 0GZ, UK
Phone: +44-1223-436900 E-mail: enquiries@crl.toshiba.co.uk
[2] Department of Physics and Astronomy, Univ. of Sheffield,
Hounsfield Road, Sheffield S3 7RH, UK
Phone: +44-114-22-23752
[3] Cavendish Lab., Univ. of Cambridge,
Madingley Road, Cambridge CB3 0HE, UK
Phone: +44-1223-337200

Abstract

The emission rate of entangled photons from cascaded, atom-like few-level systems is limited by the dynamics of the radiative transitions. Here, we overcome the equilibrium limit for a semiconductor quantum dot via an active reset of the radiative cascade. We show theoretically and experimentally the driving regime to enable the generation of entangled photon pairs with higher fidelity and emission rate than the optimum continuously driven equilibrium state. Finally, we electrically generate entangled photon pairs with a fidelity up to (95.8 ± 1.3) % at a record clock rate of 1.15 GHz.

1. Introduction

Single and entangled photons promise unique advantages for many applications in quantum photonics, including enhanced secure key rates in quantum key distribution (QKD) through elimination of multiphoton emission [1], and global scale unconditionally secure networks with entanglement-based quantum repeaters [2].

Semiconductor quantum dots (QDs) act as artificial atoms in the solid state and have been shown to emit single and entangled photons with approaching ideal properties, with the prospect of on-chip integration, and compatibility with optical fiber quantum networks. However, state-of-the-art QKD systems based on coherent laser pulses employ clock rates in the gigahertz range for high data throughput [3, 4].

Clock rates achieved with entangled photons from QDs are much lower [5, 6], intrinsically limited by the lifetime of the transitions [7, 8], impeding high frequency operation. We show that, counterintuitively, by pumping the system only for a fraction of the time, it is possible to access the superequilibrium regime and generate more entangled photon pairs compared to keeping the system in an optimum continuously driven equilibrium. This is made possible by employing a high frequency pulsed excitation regime where the cycle is reset while still highly optically active, despite a reduced emission probability per clock cycle. At the same time, this scheme maintains a superior entanglement fidelity. We expect our results will enable improved performance of a wide range of entanglement-based photonic applications.

2. Active Reset of the Quantum Dot System

In a semiconductor quantum dot, the biexciton state (XX) decays via an intermediate neutral exciton (X) superposition state, resulting in two consecutively emitted, polarization-entangled photons [9, 10]. We explore this system using a theoretical rate equation model, using experimentally measured QD parameters.

We introduce a novel active reset (AR) scheme, based on a GHz-clocked, premature reinitialization of the QD system before the population has reached the ground state. Perhaps surprisingly, we calculate the existence of a range of clock rates between 520 MHz and 3.07 GHz for which the entangled pair generation rate in AR reaches superequilibrium values, exceeding the optimum pair rate from continuous driving by up to 43%. Previous experimental demonstrations have been limited to below 500 MHz and far removed from the optimum frequency [5, 6]. Moreover, AR driving allows for a superior overall entanglement fidelity over one clock cycle of 90.9%, while the optimum equilibrium case is limited to 80.9%. Altogether, the model we present demonstrates the feasibility of overcoming the limits on entanglement fidelity and entangled-pair brightness imposed by DC or full-cycle pulsed driving.

2. Experimental Active Reset

In addition, we support the findings of the theoretical model experimentally. To enable GHz clock rates, we present a high-bandwidth, low capacitance QD light-emitting diode (LED) design that responds to very short electrical pulses <100 ps. Using this diode we demonstrate the, to our knowledge, fastest-clocked generation of single photons [7, 11], entering the "super high frequency" radio band (comprising the 3–30 GHz range [12]) for the first time.

We subsequently present a low-power, proof-of-principle implementation of the described AR regime to generate entangled photons. Fig. 1a shows the resulting fidelity to a maximally-entangled evolving Bell state [13] with the diode driven in the AR regime at 1.15 GHz. The emission reaches a maximum fidelity of (95.8 ± 1.3) % and remains above the classical limit of 50 % for the majority of the cycle, indicating electrically driven entangled pair generation at a record 1.15

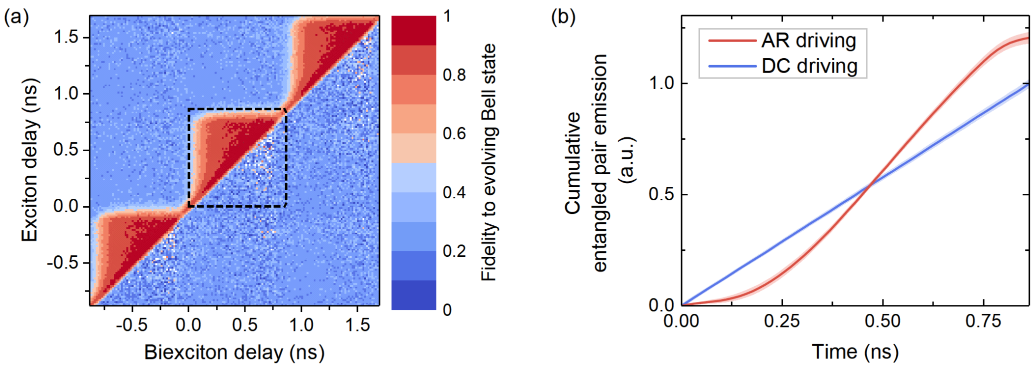

Fig. 1 Generation of entangled photon pairs via active reset at a record 1.15 GHz clock rate. (a) Fidelity to a maximally-entangled evolving Bell state as a function of biexciton and exciton emission time. The dashed black square indicates one 1.15 GHz clock cycle. In active reset, the entanglement is sharply quenched at the end of each clock cycle. (b) Cumulative entangled pair emission over time. Plotted over one 1.15GHz cycle, normalized by the overall two-photon coincidences in the respective experiment. Shaded ribbons indicate the respective estimated standard error based on Poissonian detection statistics and estimated setup drifts in polarization.

GHz clock. The overall entanglement fidelity, integrated over all photon pairs detected within the same driving cycle comes to (79.5 ± 1.1) %, sufficient for entanglement-based QKD [14, 15], and exceeds the overall fidelity of a comparison DC measurement of (71.2 ± 1.0) % for the same time window.

Finally, we compare the measured cumulative entangled photon pair intensity in AR and DC (Fig. 1b). Our measurements reveal a superequilibrium entangled-photon pair emission in AR, enhanced by (21 ± 3) % compared to continuous driving in DC. Thus, we demonstrate how resetting the QD before the system is likely in the ground state achieves a higher entangled photon emission rate than sustaining a continuously driven equilibrium.

3. Conclusions

The super-high-frequency driven (3.05 GHz) single photon LED and active reset driven (1.15GHz) entangled LED results presented above impact other quantum emitter technology, particularly those based on semiconductor QDs. For electrically driven devices, a key achievement is the high bandwidth entangled-LED mesa structure itself, which places no particular constraints on the optical device design or collection optics. The approach is therefore compatible with a wide variety of other techniques to enhance the source brightness. Entangled LEDs operated in the active reset regime may benefit the overall performance of entanglement-based photonic applications. The GHz-clocked generation of entangled photon pairs combined with the enhanced entanglement fidelity and source brightness compared to equilibrium operation is of particular interest for entanglement-based QKD protocols, quantum relays, and future implementations of a solid state quantum repeater.

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* Present address: Department of Electronic and Electrical Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD, UK