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Entangled-Photon Pair Emission from a Light-Emitting Diode

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Abstract. Electrically-driven entangled-photon generation is demonstrated for the first time using a single InAs/GaAs quantum dot embedded in a light emitting diode structure. Under alternating-current injection, we found that the entanglement fidelity was of sufficient quality for quantum information applications such as quantum key distribution.

1. Introduction

Quantum entanglement plays a central role in quantum information technology as sources of entangled-photon pairs are required for entanglement-based quantum key distribution [1] and efficient linear-optical quantum computers [2]. Existing sources of entangled-photon pairs all require a laser for optical excitation, imposing a practical limit on their potential for large-scale quantum information applications. For Poissonian sources, including the most widely used parametric down-conversion, zero or multiple-photon pairs can be emitted per laser excitation pulse due to the probabilistic nature of the non-linear process. This presents an additional fundamental limitation on large-scale systems, due to the limited success probability of quantum operations and errors. For successful future applications, these complications can be overcome with an electrically-driven on-demand source of entangled-photon pairs [3], which currently does not exist.

Here we report the realisation of the first electrically-driven source of entangled-photon pairs, which consists of a quantum dot embedded in a semiconductor light emitting diode (LED) structure [4]. We show that the device emits entangled-photon pairs under direct- and alternating-current (dc and ac) injection; the latter indicates its potential function as an on-demand source and without the need for a complicated laser driving system.

2. Experiments

2.1. Entangled-LED design and operation

Our device contains a single quantum dot, which in recent years have been manipulated to emit single pairs of entangled photons via the radiative decay of the biexciton state [5] (Figure 1 (a)). The biexciton state is formed by capture of two electrons and two holes via electrical injection. The biexciton state radiatively decays to the ground state via one of two bright-exciton states, which

determines the polarisations of the resulting pair of photons. If the fine-structure splitting between the two exciton states is close to zero then the decay path can only be determined by measuring the polarisation of the photons [6]. Consequently, the photons are entangled in polarisation and the emission is characterised by the two-photon Bell-state, $\left|\psi^{+}\right\rangle=\left(\left|RL\right\rangle+\left|LR\right\rangle\right)/\sqrt{2}$, where $\left|RL\right\rangle$ corresponds to right- and left-hand circularly polarised photons being emitted from the biexciton and exciton states, respectively.
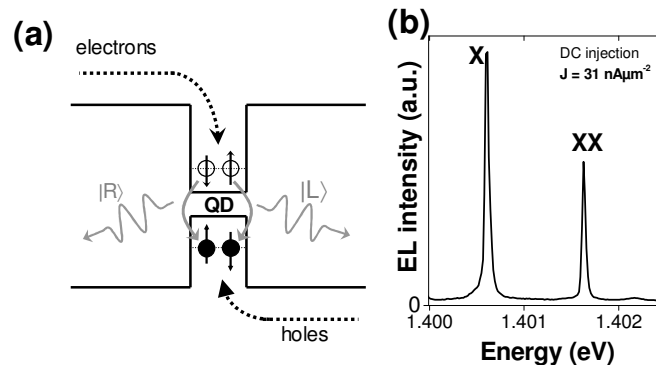

Figure 1. (a) Schematic of the active region of the entangled-LED showing the emission of a polarisation entangled-photon pair via the biexciton cascade. Here the diode is in its 'off' state, just after non-resonant electrical injection of two electrons (open circles) and two holes (closed circles) into the quantum dot. (b) CCD-recorded electroluminescence (EL) spectrum of the quantum dot investigated in this report using dc electrical injection with current density (J) = 31 nAµm^{-2}.

The design of the LED is based on a single layer of quantum dots embedded in a *p-i-n* doped planar microcavity. Details of device growth, by molecular beam epitaxy, and fabrication can be found in reference [4]. Two features of the design are crucial to successful operation as an entangled-LED. The first is an unusually thick cavity (2λ) and intrinsic region (~ 400nm). This is to suppress electrons tunneling into the dot from the n-doped region during biexciton decay, thereby minimising destruction of entanglement after emission of the first photon caused by charging of the intermediate exciton state and maximising the amount of light emitted from the neutral excitonic states. Secondly, careful control of the growth conditions created InAs quantum dots emitting ~ 1.4eV, which are suitable for entangled-light generation due to their very small fine-structure splitting [5][7].

Carrier injection into the quantum dots is achieved by biasing the diode beyond its turn-on voltage. We studied a quantum dot in our device which had almost zero fine-structure splitting, with magnitude 0.4±0.1µeV [8]. Its 5K electroluminescence (EL) spectrum is shown in Figure 1 (b), with emission from the exciton (X) and biexciton (XX) states labelled. The emission lines were identified by power dependence, time-resolved EL, and correlation measurements [9].

2.2. dc experiment

Photons from the X and XX transitions were resolved in polarisation and in time in order to measure the co- and cross-polarised second order pair-correlation functions $g_{XX,X}^{(2)}(\tau)$ and $g_{XX,\overline{X}}^{(2)}(\tau)$, where τ is the time delay between the XX and X photons [10].

Figure 2 shows the measurement of $g_{XX,X}^{(2)}(\tau)$ and $g_{XX,\overline{X}}^{(2)}(\tau)$ in the rectilinear (a), diagonal (b) and circular (c) polarisation bases when a direct current with density 31 nAµm^{-2} was injected into the

device. The co-polarised (VV) correlations in Figure 2 (a) show the characteristic shape of a radiative cascade. We expect the emission of an exciton photon to follow the emission of a biexciton photon. As a result, $g^{(2)}_{XX,X}(\tau)$ is increased for small positive delays and suppressed for small negative delays. Away from $\tau = 0$ $g^{(2)}_{XX,X}(\tau)$ and $g^{(2)}_{XX,\overline{X}}(\tau)$ both tend to 1 due to uncorrelated emission events. A dip is seen for cross-polarised pairs (HV) in Figure 2 (a) due to the selection rule that the cascade must produce pairs with the same linear polarisation. Similar correlation behaviour is seen for photon pairs polarised in the diagonal basis in Figure 2 (b). Significantly we see the opposite correlation behaviour for circularly polarised photon pairs (Figure 2 (c)) than in the linear and diagonal cases. This is expected for entangled-photon pairs in the Bell state $|\psi^+\rangle$ [5][10], as the two-photon wavefuntion can be expressed as the superposition of co-linearly, co-diagonally or cross-circularly polarised photon pairs.
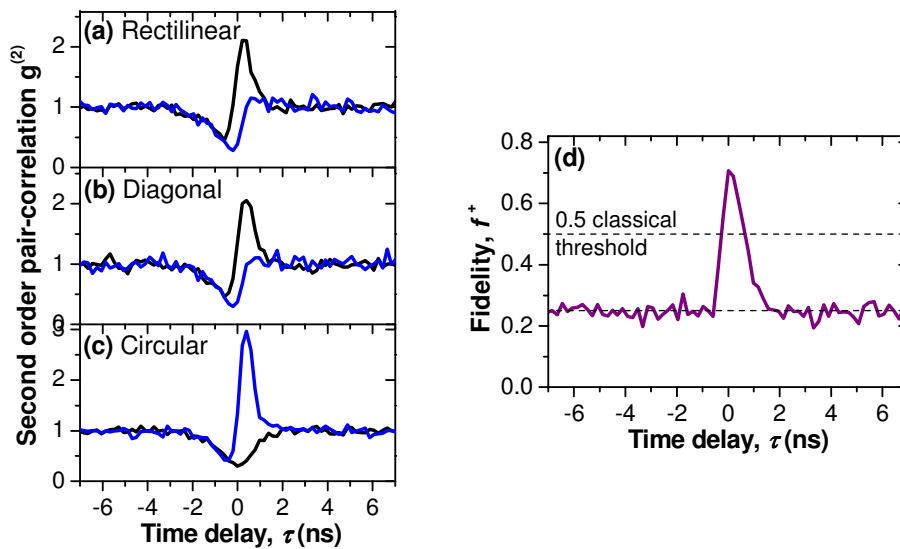

Figure 2. Polarised pair-correlation results from dc electrical injection into the LED. $g^{(2)}_{XX,X}(\tau)$ and $g^{(2)}_{XX,\overline{X}}(\tau)$ measured in the (a) rectilinear, (b) diagonal and (c) circular bases. Correlations measured for photons of the same (orthogonal) polarisation are shown in black (blue). (d) Fidelity, f^+, as a function of time delay, τ.

The entanglement fidelity (f^+) of the emitted light, projected onto the maximally entangled state $|\psi^+\rangle$, is plotted in Figure 2 (d). The fidelity was determined directly by combining correlations measured in the rectilinear, diagonal and circular polarisation bases [6]. The peak at $\tau = 0$ gives a maximum dc fidelity $f^+= 0.707 \pm 0.023$. This exceeds the 0.5 threshold for a source emitting a classically polarisation-correlated state by 9 standard deviations, proving that entangled photons have been electrically generated for the first time. The measured fidelity is limited by several factors [6], including the timing jitter on the photon detectors and re-excitation of the quantum dot part way through the cascade.

2.3. ac experiment

Figure 3 shows the results of polarised photon-pair correlation experiments conducted when the device was pulsed with an alternating current at a repetition rate of 80MHz. As in the dc case above, for

entangled-photon pairs in the Bell state $\left|\psi^+\right\rangle$ we expect to measure co-polarised photon pairs in the rectilinear and diagonal bases and cross-polarised photon pairs in the circular basis. Figure 3 (a) shows the measurement of $g^{(2)}_{XX,X}(\tau)$ and $g^{(2)}_{XX,\overline{X}}(\tau)$ in the rectilinear (a), diagonal (b) and circular (c) polarisation bases. The dominant peak at zero time delay in each of these traces has a higher number of coincidences than the others, corresponding to emission of an X photon shortly after a XX photon. In both Figure 3 (a) and (b) this large peak belongs to the co-polarised trace, indicating measurement of co-polarised photon pairs in the rectilinear and diagonal bases. In contrast the cross-polarised peak dominates in Figure 3 (c), indicating measurement of cross-polarised photons pairs in the circular basis. This data gives a peak ac fidelity of $f^+ = 0.785 \pm 0.022$. This ac fidelity is larger than the dc fidelity (0.707) presented above in Figure 2 (d). This direct comparison is possible as the timing resolution is the same in both experiments at 0.2 ns. It is likely that the ac fidelity is larger due to the lower level of re-excitation of the quantum dot when driven by a short voltage pulse.
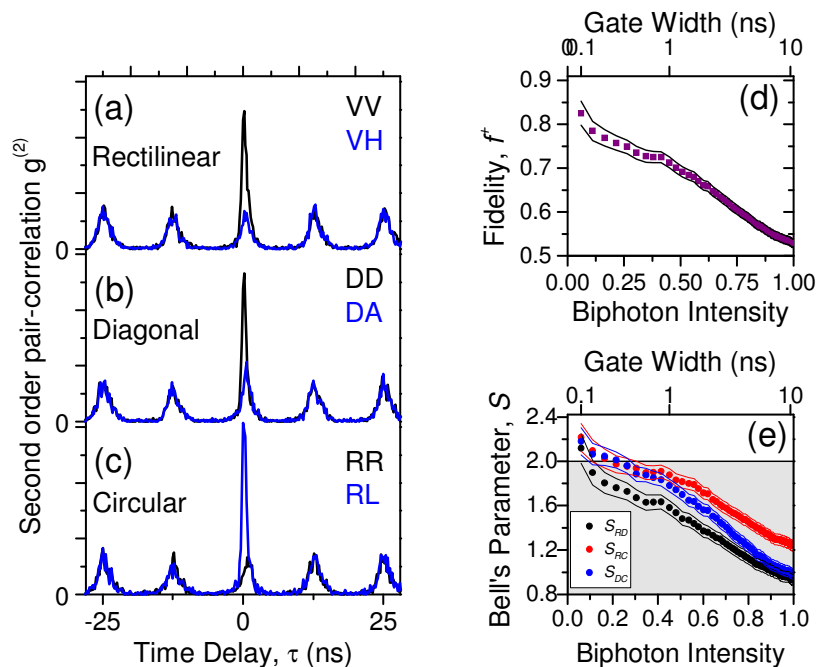

Figure 3. Polarised pair-correlation results from ac electrical injection into the diode. $g^{(2)}_{XX,X}(\tau)$ and $g^{(2)}_{XX,\overline{X}}(\tau)$ measured in the (a) rectilinear, (b) diagonal and (c) circular polarisation. (d) Fidelity and (e) Bell's parameters at $\tau = 0$ as a function of the proportion of the total biphoton intensity that is analysed. The biphoton intensity is varied by changing the gate width (top axis).

The entanglement fidelity available to an application may be enhanced by limiting the time the detectors remain active. We explore this possibility in Figure 3 (d) by changing the gate width used in the measurement of f^+. For the zero period, gate width is defined as the maximum permitted time delay between the two photons to register a detection event. This changes the proportion of the detected biphotons to be accepted in the measurement of f^+. Without rejecting *any* detected photon pairs (i.e. biphoton intensity = 1.0), $f^+ = 0.530 \pm 0.010$, which is above the classical threshold of 0.5, proving entangled-light emission. The fidelity rises quickly as the proportion of biphoton intensity accepted is

reduced. This leads to a maximum ac fidelity of $f^+ = 0.826 \pm 0.027$, when 6% of biphoton coincidences closest to $\tau = 0$ are accepted (0.1ns gate width).

Using these results it is also possible to determine Bell's parameters within a quantum mechanics framework [8]. The three different Bell parameters measured here, S_{RD}, S_{DC} and S_{RC} defined in reference [8], are non-equivalent and correspond to three different planes of the Poincaré sphere. A value greater than 2 for any of these parameters represents a violation of Bell's inequality on the corresponding plane. Figure 3 (e) displays these three Bell parameters measured as a function of the biphoton intensity (bottom axis) and gate width (top axis). Bell's parameters increase as we decrease the gate width due to an improving degree of correlation in all three polarisation bases. S_{RD} is less than S_{RC} and S_{DC}, as the circular basis has the highest degree of correlation. At the smallest gate width of 0.1ns we find; $S_{RD} = 2.12 \pm 0.13$, $S_{DC} = 2.18 \pm 0.12$ and $S_{RC} = 2.22 \pm 0.12$. The latter two violate Bell's inequality by more than one standard deviation. Overcoming this threshold shows that the entangled-LED is of high enough quality for applications such as a quantum relay and entanglement-based quantum key distribution [1].

3. Conclusions

We have eliminated the need for large and complicated laser driving systems in future quantum information applications by demonstrating high fidelity entangled-light emission triggered from an entangled-LED. Entangled-photon pairs with such high fidelity are sufficient for teleportation [12] and entanglement swapping [13], which are important components in a quantum computer. Improvements to the LED such as reducing the background light emission [10][14] and increasing the speed of the device to minimise re-excitation during pulsing could be made to push the fidelity even higher to eventually realise electrically-operated fault-tolerant quantum computing.

4. Acknowledgements

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