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Biexciton cascade in telecommunication wavelength quantum dots

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Biexciton cascade in telecommunication wavelength quantum dots

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Abstract.
We report on polarisation correlation from the cascaded recombination of biexcitons in a quantum dot emitting at a telecommunication wavelength. The fine structure splitting of the exciton state in this InAs/GaAs quantum dot is of the order of 100 μeV and polarisation correlation is expected. Strong polarisation correlation between the biexciton and exciton emission lines is observed under both continuous wave (CW) and pulsed laser excitation so telecom wavelength quantum dots with lower energy splittings could be suitable for entangled photon pair generation. Measurements were performed using nanowire superconducting single photon detectors (SSPDs). SSPDs offer low time-jitter and improve the resolution of features in the correlation spectra, including the asymmetric dip and peak resulting from the cascaded emission with the peak extending more than an order of magnitude above the Poissonian level.

1. Introduction

The biexciton cascade in quantum dots has been shown to be useful for the generation of pairs of photons and in particular for the creation of pairs where the polarisations of the two photons are related. The linear polarisations of the two photons can be correlated [1–4] or the polarisations of the photons can be entangled [5–7]. For many network applications the emission must be at a wavelength compatible with standard optical fibre [8–10]. We have previously demonstrated the use of single photons to distribute keys securely over an optical fibre link [11] but for more complex networks, or to extend communication lengths using quantum repeaters, sources of entangled photon pairs are desired. Polarisation correlated photon pairs have also been proposed for direct use in passive quantum key encoding [1].

2. Sample

Quantum dots were grown to have a bimodal dot size distribution as described previously [8]. The growth includes a strain relaxing layer of InGaAs above the quantum dots to extend the emission wavelength to $\sim 1.3\,\mu$m. The nominal indium composition of this layer is $\sim 19\,\%$ and it is hoped that the number of structural defects introduced by this layer is not so high as to substantially degrade the important properties of the quantum dots, such as the radiative emission efficiency or the spin-scattering rate. The dots are also physically larger and have significantly different confinement potentials than those at shorter wavelengths, so it is interesting to verify whether strong polarisation correlation can be observed in this system.

3. Photoluminescence spectroscopy

Figure 1 shows photoluminescence spectra from the sample for each polarisation. Two doublets are clear at wavelengths ~ 1289.8 nm and ~ 1299.9 nm corresponding to emission from the exciton and biexciton states respectively. The fine structure splitting is determined to be $\sim 100\,\mu$eV. With such a large splitting we expect to be in the regime of polarisation correlation but not polarisation entanglement.

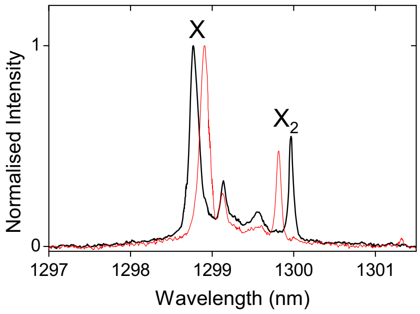

Figure 1. Photoluminescence spectra recorded for two orthogonal polarisations. Doublets arising from exciton (X) and biexciton (X_2) emission are both visible. A few weaker emission lines are present between the X and X_2 emission. Their origins are not known but could include other quantum dots or other (charged) excitonic complexes from the same dot.

4. Superconducting single photon detectors

The superconducting nanowire detectors employ a meander-type geometry defined in a niobium nitride film and were operated around 4 K in a closed cycle cooling system [12, 13]. The performance of the detectors is shown in the left of figure 2. During the measurements the detectors were operated around the 1–2 % efficiency region in order to maintain low dark count levels.

To measure the response function of the correlation system we used light from a synchronously pumped optical parametric oscillator, delivering picosecond pulses at a wavelength of 1300 nm. This light was passed to both superconducting detectors and correlations between detection events in the two detectors were recorded. The resulting correlation is shown in figure 2 along with a Gaussian fit to the data (red) with a width of 127 ps. The data are well represented by the Gaussian fit due to the simple temporal response of the superconducting detectors.

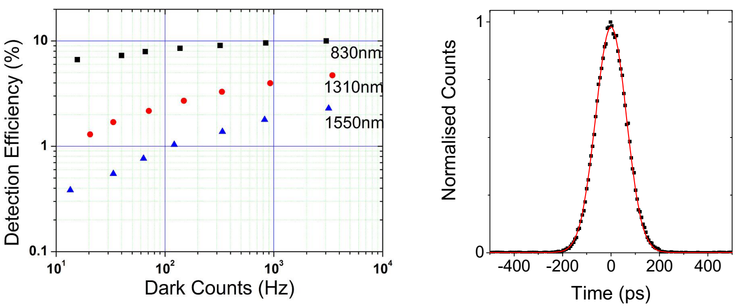

Figure 2. (Left) Detector efficiency vs dark count rate. (Right) Response of the correlation system comprising the pair of superconducting single photon detectors and associated electronics.

5. Continuous wave cross-correlations

Correlation measurements were first performed under excitation by continuous wave laser excitation from a semiconductor diode laser at 1064 nm. Independent tuneable spectral filters were used on each channel to select emission from either the exciton or biexciton onto the two superconducting detectors. The delays between coincidence counts were analyzed using a single time-to-analogue converter and the results are shown in figure 3. The left hand plot represents the case where the same polarisation state was passed to each detector and the right hand plot represents orthogonal polarisations. A strong asymmetry is seen about zero delay reflecting the cascaded nature of the emission. For same-polarisations the peak observed at small positive delay extends more than an order of magnitude above the Poissonian level. The large height measured for this peak is made possible by the excellent time resolution of the detection system.

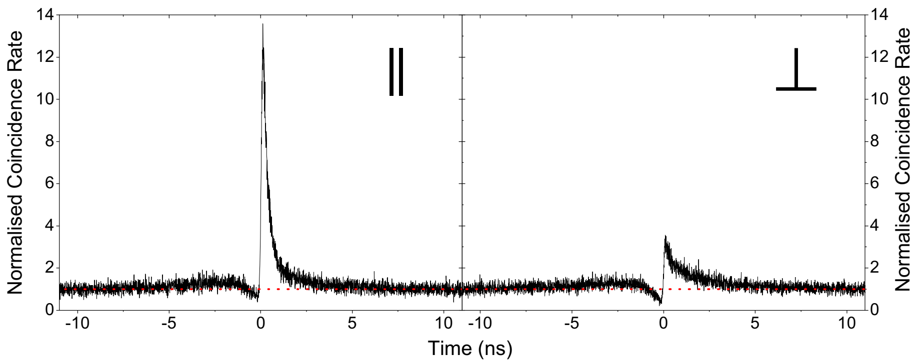

Figure 3. Exciton–biexciton cross-correlations between same (||) and orthogonal (⊥) polarisations under continuous wave excitation. The correlation measurements were performed with the sample at 40 K.

In the cross-polarisation data a peak is still seen for small positive time delay but its height is greatly reduced with respect to that of the same-polarisation data. Imperfect polarisation alignment is likely to have been a significant factor giving rise to the peak in the cross-polarisation data. The fact that the dip at negative delay does not reach zero is due to a combination of detector dark counts, background emission from other states in the system, any residual laser light from the excitation pump laser and jitter of the detection system. The dip is expected to fall to zero immediately adjacent to the very strong correlation peak. Although the jitter of the detection system is rather low, a strong correlation peak can impact the depth of the measured dip and the effect will be larger for the same- than for the cross-polarisation data.

A weak bunching effect is also observed in the data. This is seen most clearly where the correlation curve rises above the Poissonian level for a range of negative time delays. Such a bunching effect can increase the height of a correlation peak close to zero delay but we note that it should scale both the same- and cross-polarisation data similarly.

6. Pulsed cross-correlations

The sample was excited at a wavelength of 1064 nm by a picosecond pulsed laser diode at 50 MHz. The correlation data are shown in figure 4. Again a strong correlation peak is seen in the same-polarisation data. Note that the zero-delay peak is asymmetric due to the nature of the cascade. The area of peaks in the pulsed data can be integrated to obtain a measure of the strength of the polarisation correlation. We define an approximate degree of correlation, C, as

$$C = \frac{g_{\parallel}^{(2)}(0) - g_{\perp}^{(2)}(0)}{g_{\parallel}^{(2)}(0) + g_{\perp}^{(2)}(0)}, \tag{1}$$

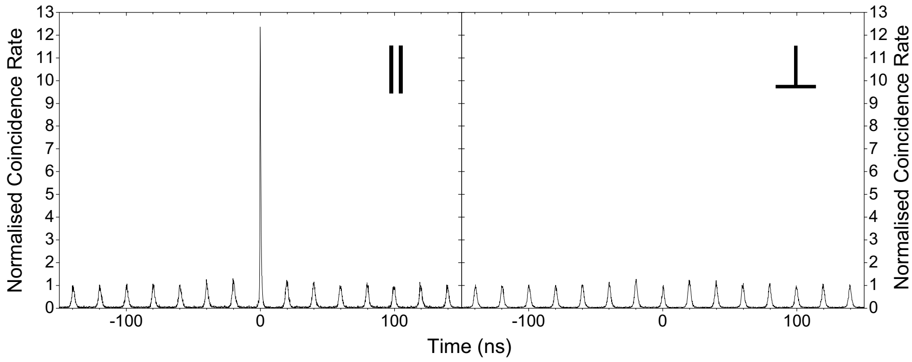

Figure 4. Exciton–biexciton cross-correlations between same (‖) and orthogonal (⊥) polarisations under pulsed excitation.

and, with $g^{(2)}_{\parallel}(0) = 4.08$ and $g^{(2)}_{\perp}(0) = 0.85$ referenced to the area of the average of the large finite delay peaks, we obtain $C = 0.65$. No corrections have been made to account for dark counts in the detectors and it is likely that imperfect polarisation alignment was also limiting the measurements. Some emission from other states will also have been passed by the spectral filters. However, the degree of correlation here is of the same order as measured at shorter wavelengths in [2].

7. Conclusion

Strong polarisation correlation between photon pairs from a quantum dot biexciton cascade has been demonstrated at a wavelength $\sim 1.3\,\mu$m. Superconducting nanowire detectors offering low temporal jitter enable good resolution of features in measurements using both continuous wave and pulsed laser excitation. The high degree of polarisation correlation measured suggests the absence of scattering processes strong enough to prevent the observation of entangled photon pair generation from similar quantum dots with smaller fine structure splittings.

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