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# Single-photon sources with optical fibre integration

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**Abstract.** We report a ‘plug and play’ single-photon source based on single quantum dots with an integrated optical fibre output. We attach an optical fibre to the sample surface in order to measure single-dot photoluminescence, which avoids the light coupling between quantum dots and free space. The excitation light (a HeNe Laser) is coupled into the optical fibre to excite the quantum dots, and the emitted photoluminescence is collected with same optical fibre. To verify the emission of single photons, correlation measurements of the luminescence were performed using a Hanbury Brown and Twiss setup with a 50/50 beamsplitter and two single-photon-counting avalanche photodiodes. Clear antibunching with the second-order correlation function at zero time delay less than 0.1 indicates single-photon emission. The devices are stable, and reproducible for an arbitrarily long time, which is very promising for real implementations of quantum key distribution and linear optical quantum computation.

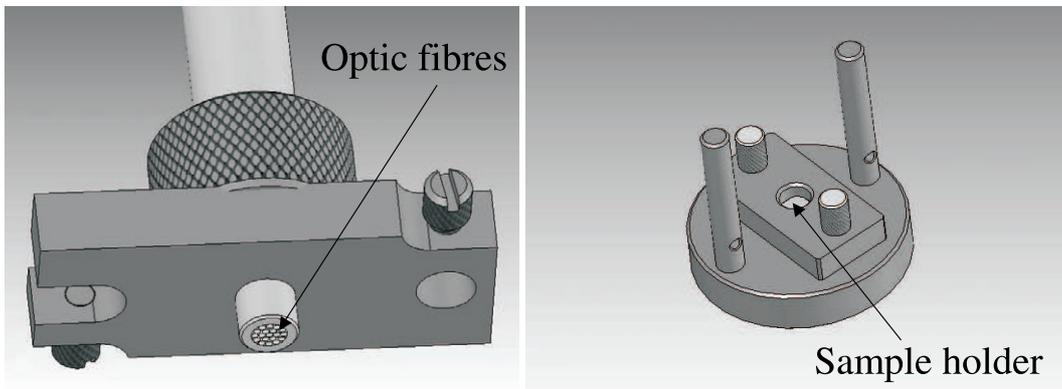
## 1. Introduction

To implement quantum communications, single-photon sources are desirable to provide secure quantum key distribution [1, 2]. Semiconductor quantum dots have been investigated intensively to obtain optically [3] or electrically [4] pumped single-photon sources. Those experiments used confocal microscopy systems in which large numerical aperture objectives have been used to focus the excitation light, and to collect the emission light from quantum dots. The samples were usually mounted on cold finger cryostats. Because of mechanical vibrations and temperature fluctuations of the system, the intensity and emission energy of the quantum dots are not stable in the time domain. Therefore, new designs for stable single-photon sources are desirable. Attaching an optical fibre to a quantum dot wafer is one of the methods to avoid these problems [5, 6, 7].

The principal application of single-photon sources is to integrate them into fibre optic networking [8], although free space quantum cryptography is also desirable [9]. Most of the optical fibre based single-photon sources in quantum cryptography are highly attenuated lasers, in which the average photon number per pulse is significantly less than one. The number of photons in these pulses are described by Poissonian statistics, so there is a possibility that there are multiple photons in one pulse. Therefore, single-photon sources with optical fibre integration are in demand for applications in quantum communications. In this work, we report a stable single-photon source with optical fibre integration from InGaAs quantum dots.

## 2. Experimental methods

Normally the fibre is glued on the top of the quantum dot wafer with an ultra-violet light curing optical adhesive [5, 6, 7]. To obtain single dot emission through a fibre with a mode field size around  $5\ \mu\text{m}$  in diameter, the dot density should be extremely low. However, the low dot density induces a low yield of working fibres, from which single dot emission can be observed. The dot density of the wafer in this work is less than  $0.1\ \text{dot}/\mu\text{m}^2$ . To avoid this problem, we used a bundle of optical fibres (around 600) binding together in one end and polished, as shown in the left panel of figure 1. The polished end of the fibre bundle is mounted to the sample holder (right panel of figure 1) without optical adhesive. All fibres in the other end were free and mounted on a fibre holder for excitation and signal collection. The sample holder was dipped into a liquid helium dewar with a temperature of 4.2 K.

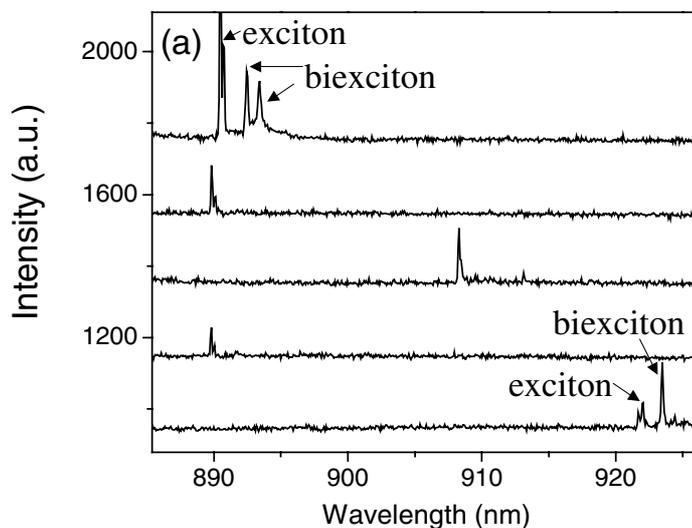


**Figure 1.** Sketch of sample holders with optical fibres attached.

The quantum dots were excited with a HeNe laser. The emitted light was collected with a collimating lens, dispersed through a 0.55 m spectrometer, and detected with a cooled charge coupled device camera. Correlation measurements of photoluminescence (PL) were performed using a Hanbury Brown and Twiss setup [10] with a 50/50 beamsplitter and two single-photon-counting avalanche photodiodes (APDs). The two APDs were connected to start and stop inputs of a time-to-amplitude converter, whose output was stored in a time-correlated photon-counting card. The resulting histograms show the large number of photon pairs with arrival time separations of  $\tau = t_{start} - t_{stop}$ . The histograms are equivalent to the second-order correlation function  $g^{(2)}(\tau)$  when  $\tau$  is much shorter than the average time between detected photons. The time resolution of the correlation card is around 47 ps.

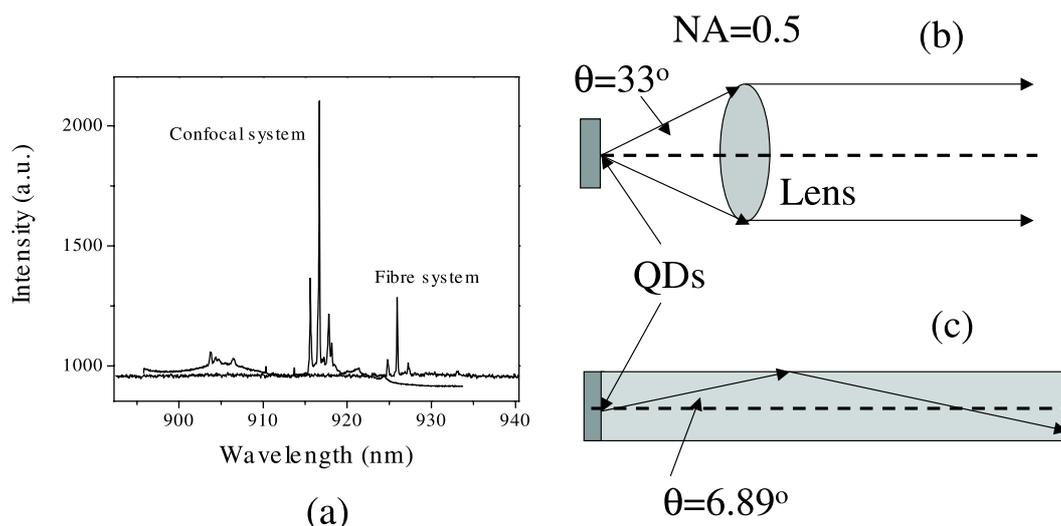
## 3. Results and discussion

Figure 2 shows the PL spectra from different fibres in the same bundle. Sharp peaks can be clearly observed from single quantum dots, due to the exciton recombination. With different excitation powers, biexciton recombination from certain fibres can be observed at the low energy side of the exciton, as shown in the bottom trace in Fig. 2. The top trace in Fig 2 shows a splitting in the exciton and biexciton emission at zero field, which is due to the in-plane exchange interaction in asymmetric quantum dots [5]. The PL intensity from the fibre is lower than that measured with a conventional Micro-PL confocal system on the same wafer. Figure 3 (a) shows the two typical PL spectra for both systems keeping other measurement conditions similar. To explain the reason for the reduced intensity with the fibre, we ran a simple simulation for the in-plane wave propagation mode. A sketch of the optical paths are shown in figure 3 (b) and (c). We neglected the air gap between the fibre and the GaAs wafer for the fibre system. With the Fresnel formula, the intensity coming from the GaAs surface to the fibre is about 7 times higher



**Figure 2.** Photoluminescence from single quantum dots with different optical fibres in a single fibre bundle.

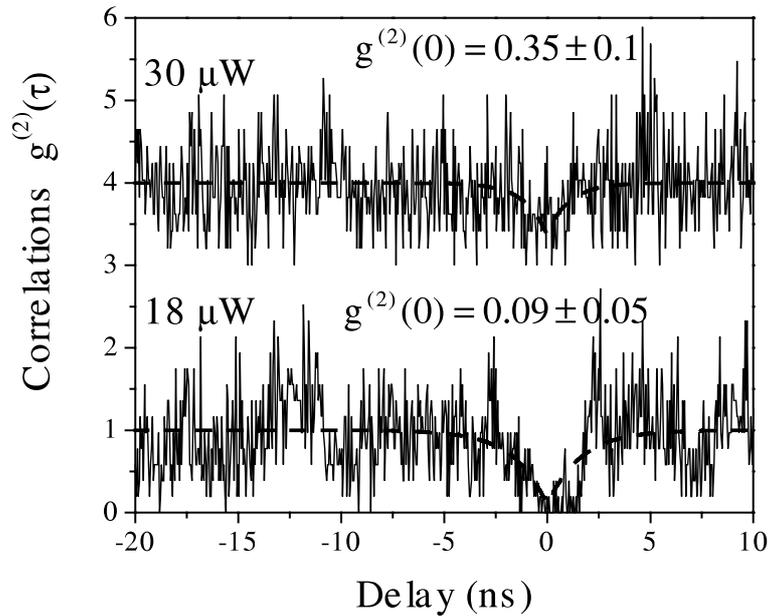
than that to free space because the refractive index of the fibre is around 1.44, while that for air is 1. From the GaAs surface, the light is collected using an objective with a numerical aperture of 0.5 in the confocal system, while the numerical aperture for the guided fibre is around 0.12. The apex angles of the cone where the light is detected are  $6.89^\circ$  and  $33.3^\circ$  respectively for the fibre and the confocal systems; the amount of light collected by the objective is 22 times higher than by the fibre. Therefore, the intensity collected from fibres is 3 times lower in total, which corresponds well to what we observed in Figure 3(a).



**Figure 3.** (a) Typical PL spectra of the two systems with 1 s integration time. (b) Sketch of the optical path for confocal system and fibre system.

To avoid the excitation laser and wetting layer emission being fed in the single-photon detectors, narrow bandpass interference filters have been used to obtain a single emission peak

from an exciton. The single peak was used to perform correlation measurements. Figure 4 shows the second order correlation function  $g^{(2)}(\tau)$  of the single dot emission with different excitation powers. With a power of  $18 \mu\text{W}$ ,  $g^{(2)}(0)$  (the  $g^{(2)}(\tau)$  at zero time delay) is  $0.09 \pm 0.05$ , which clearly shows the antibunching nature of single photons. For an ideal single-photon emission,  $g^{(2)}(0)$  should be equal 0. The reason why  $g^{(2)}(0)$  does not equal 0 is due to dark counts. With increasing excitation power, the dip at zero time delay is shallower, due to biexciton formation which could not be filtered with our filter. The dashed thick lines show the fitted results. Unfortunately we cannot estimate the lifetime of the exciton emission because of the dispersion of the optical fibre.



**Figure 4.** Second-order correlation function  $g^{(2)}(\tau)$  measured (thin lines) and fitted (thick line) of single excitonic PL peaks with different excitation powers.

#### 4. Conclusion

We have demonstrated single-photon emission via an optical fibre, which was steadily mounted on the top of a quantum dot wafer. The second order correlation function at zero time delay is less than 0.1 which clearly shows single photon emission. The devices are stable, and reproducible for an arbitrarily long time, which is very promising for a real implementation of quantum key distribution and linear optical quantum computation.

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