Abstract:
In this lab we investigated the quantum dot excitation method of single photon production. Objectives included preparing quantum dot samples in a liquid crystal solution, successfully imaging fluorescence emission from quantum dots using a confocal microscope setup, and verifying antibunching using a Hanbury Brown and Twiss setup. We learned how to use a confocal microscope setup to image fluorescence using both a CCD and APDs. We successfully demonstrated antibunching by building a histogram of photon separation times and showing that no photons were arriving simultaneously.

1. INTRODUCTION AND THEORETICAL BACKGROUND:
The theoretical framework supporting quantum cryptography has largely been put in place. Significant practical challenges, however, must be overcome if quantum cryptography is to become a reality. Among these challenges, the reliable production of single photons has emerged as a central problem. Several different methods of single photon production have been proposed and investigated in the past. In this lab we investigate the quantum dot excitation method of single photon production.

Traditionally single photons have been produced by greatly attenuating a laser source (using filters). The problem with this approach is that there is no guarantee that photons will arrive only one at time. An antibunched single photon source guarantees photons separated in space and time. In order to verify antibunching, it must be shown that no photons are arriving simultaneously. By measuring and analyzing the time gaps between incoming photons, we can create a statistical histogram that will show antibunching if it is present. In order to measure the time gaps between incoming photons, we used a Hanbury, Brown and Twiss setup. Incoming photons from the fluorescing sample were split into two channels (one for each APD). The electrical signals generated by incoming photons were then compared. When \( g(0) < 1 \) (from the following equation) then we have a quantum mechanical case. In classical situations \( g(0) > 1 \). In this case \( g \) represents the second order (temporal) coherence of the intensity counts at each APD.
In order to observe quantum dot fluorescence a confocal microscope setup was used. A confocal microscope has the advantage that any object out of the imaging plane is not imaged, thus allowing for a very narrow vertical area of the sample to be imaged. This is achieved using a pinhole which limits the imaging of off axis rays. The advantage of using a confocal microscope is that off axis QD are not imaged, thereby increasing the likelihood of observing antibunching.

Liquid crystals were used in this lab to select for a specific polarization state. Because liquid crystals are a photonic band gap material, the emission of light from quantum dots embedded in a cholesteric liquid crystal medium is suppressed at wavelengths in the stop band. Thus spontaneous emission from quantum dots is suppressed. The chiral tails of the cholesteric liquid crystals result in close alignment of the liquid crystal molecules. When quantum dots are embedded in a liquid crystal medium, this leads to a greater likelihood of achieving antibunching.

Our setup for this lab consisted of a green 532 nm laser source which was directed to a sample of quantum dots. Light from quantum dot fluorescence was then directed to either a CCD camera or a pair of avalanche photo diodes (APDs). A dichroic mirror was used to keep light from the laser from entering the imaging systems (see FIG 1). The Hanbury Brown and Twiss setup consisted of two APDs connected to a TimeHarp card and a computer. A 50/50 beam splitter was used to direct incoming photons to both APDs (see FIG 2)

\[ g^{(2)}_{T,R}(0) = \frac{\langle \hat{n}_T(\hat{n}_R - 1) \rangle}{\langle \hat{n}_T \rangle^2} = g^{(2)}_{I,I}(0) = g^{(2)}(0) \]

2. PROCEDURE
1. We calibrated the photon counting setup.
2. We measured the intensity of the laser beam to be ~ 100-105 microwatts.
3. We prepared the QD samples by placing a drop of low concentration 705nm QD solution onto a spinning microscope cover slide in order to achieve uniform
distribution. One sample was prepared with QD only, while the other was mixed with liquid crystal in order to control spontaneous emission by selecting for a specific polarization. Each of the following steps was performed with both samples.

4. We placed the samples (one at a time) on the confocal microscope objective with a drop of oil between the slide and the objective. The slide was held in place using magnets.

5. A 532 nm laser was run through a spatial filter and then expanded before being focused on the sample.

6. Light fluorescing from the sample was collected using a dichroic mirror which reflected light from the laser but allowed light at the fluorescence wavelength of 705nm to pass through.

7. An internally cooled CCD camera was used to create initial images of the quantum dots, as well as videos.

8. We focused the microscope and moved the sample as necessary to locate fluorescing QD. FIG. 3 shows an image of fluorescing quantum dots that was taken using the cooled CCD camera.

FIG. 3 – CCD image of fluorescing 720nm quantum dots.
9. Further images were acquired using two Avalanche Photo Diodes (APD) and a nano-drive scanning apparatus. We scanned a 25x25um area of the sample in order to locate the most promising areas for antibunching (areas that appeared to contain single quantum dots). FIG 4 shows a scan of a 25x25 micron area of a quantum dot sample. Notice the striping. This is caused by blinking quantum dots.

10. We rescanned the sample in a 5x5um area. During scans we occasionally refocused, looking for sharp dips and peaks in the red and green photon count indicators. FIG. 5 shows a single line scan of the sample. Sharp peaks such as at the 12500 nm indicate a quantum dot or quantum dot cluster.
FIG. 5 - Single Line APD Scan, 25x25μm, 705nm QD.

11. A Hanbury, Brown and Twiss setup incorporating two APDs was used to measure the time gaps between incoming photons.

12. We used a Timeharp card to build histograms of recorded interphoton times.

RESULTS AND ANALYSIS

On many occasions we successfully located fluorescing QD and built histograms from 25x25μm, 5x5μm and 3x3μm scans, but were unable to observe antibunching. This may have been due to clumping of quantum dots. FIG 6 shows a histogram that is typical of bunched light. Notice that there are no distinct dips or peaks in the histogram.
On this particular occasion we were unable to observe antibunching. As can be seen in the above histogram, there is no time gap with fewer photons arriving.

In the above histogram (FIG 7) antibunching is more obvious. We see a pronounced dip in the photon count around 60ns. This indicates a decreased probability for photons to arrive at a specific time interval with respect to other photons. Although here the time interval appears to be 60ns, this is actually the zero point for our photon time interval counting. This indicates that antibunching has occurred and that no photons are arriving simultaneously.

We also were able to calculate the fluorescence lifetime of DiI dye by building a histogram which measured the time intervals between the output of a laser pulse and fluorescence. Since the fluorescence lifetime is related to the trend curve, we can easily calculate the fluorescence lifetime by taking the inverse of the time coefficient, in this case -0.2921. Thus we get 3.42 ns as the fluorescence lifetime of the QD. FIG 8 shows the fluorescence lifetime of the DiI dye molecules along with an exponential curve that was fit to the data.
DISCUSSION AND CONCLUSION

Achieving antibunching is the first step towards being able to produce single photons that would be usable for quantum cryptography. We were successful in creating and demonstrating antibunched photons, although there are several things which may have contributed to the difficulty we encountered when trying to do so. One problem may have been that quantum dots tend to clump together when in solution. When scanning fluorescing quantum dots it is essential to find single quantum dots in order to observe antibunching. This is because when there are two or more quantum dots in a cluster more than one photon can arrive simultaneously, whereas when there is only a single fluorescing quantum dot antibunching directly follows.

We found that it is possible to generate antibunched photons using fluorescing quantum dots, but that such a setup is relatively unreliable and has a long way to go before it can be used in a quantum cryptography system. Use of liquid crystal is helpful to suppress light from spontaneous emission, but does not always immediately result in antibunching being observed. We also occasionally encountered problems with having the samples in focus. This also could have contributed to increased difficulty observing antibunching.
Due to the high sensitivity of the APDs and CCD camera, all work was conducted in the dark. On several occasions, however, sudden high photon counts were observed with the APD. The source of these counts are uncertain.

REFERENCES