Lab. 3-4. Experimental observation of single-emitter fluorescence and photon anti-bunching

Laboratory Report

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Abstract: Fluorescence from single emitters, such as DiDye molecules and CdSe quantum dots, is studied extensively using confocal microscopy and Hanbury-Brown-Twiss setup. Characteristic blinking and bleaching are observed dynamically. Fluorescence lifetimes of the two single photon emitters in various hosts are measured. For the first time, photon anti-bunching is observed from CdSe quantum dots in cholesteric liquid crystal host.

I. Introduction

Over the past few decades, significant effort has been invested towards realizing systems for quantum information in the form of quantum communications and quantum computing. Non-classical photon sources are required to develop these systems, and single-photon sources (SPS) could be one of the solutions. SPS can produce photons with quantum characteristics, called photon anti-bunching effects, [1,2] and the created single photon can prevent any potential eavesdropper from intercepting a message without the receiver noticing or can be used for quantum computers. [3]

Heavily attenuated laser source and single atoms and ions at low temperature have been considered as a SPS, but their practical development is notoriously difficult since the probability of getting two photons is not zero, the system to excite single atom is often complex and has the low collection and excitation efficiencies.[4] Fluorescent light from a single emitter has been the focus of great attention using confocal fluorescence microscopy, and the confocal fluorescence microscopy can collect fluorescence light from only a single emitter.[5] A single dye molecules or single quantum-dot (QD) must be isolated and excited to cause fluorescence. In addition, we can obtain the emitted single photons on demands using triggered pump sources.

In the present paper, single colloidal semiconductor CdSe quantum dots and single DiDye molecules are excited with a pulsed diode-pumped solid state laser. The molecules and QDs are spread on a microscope slip substrate or imbedded in a polymer host (PMMA) or cholesteric liquid crystal (LC) hosts. Fluorescence was observed using a cooled EM-CCD camera or avalanche photodiode (APD) single photon counting modules. To determine the
 photons quantum property of photon antibunching, we use the Hanbury Brown and Twiss experiment with two APDs and a TimeHarp 200 photon counting PCI computer card was used in a start-stop regime with a 23 ns delay in a stop channel to create antibunching histograms.

II. Theory

We follow the derivation of the expression of coherence functions in reference [6]. It is well known that in classical coherence theory the first-order normalized mutual coherence function is given by

$$\gamma^{(1)}(x_1,x_2) = \frac{\langle E^*(x_1)E(x_2) \rangle}{\sqrt{\langle |E(x_1)|^2 \rangle \langle |E(x_2)|^2 \rangle}},$$

which is proportional to the fringe visibility of an interference pattern. $E(x_i)$ is the complex field through the $i$th pathway.

In quantum theory, the complex field can be described as a quantized electric field operator using the dipole approximation $(|\mathbf{k} \cdot \mathbf{r}| \ll 1)$ as

$$\tilde{\mathbf{E}}(\mathbf{r},t) = \mathbf{E}^{(+)}(\mathbf{r},t) - \mathbf{E}^{(-)}(\mathbf{r},t) = i \sum_{k} \left( \frac{\hbar \omega_k}{2e_0 V} \right)^{1/2} \mathbf{e}_k [\tilde{a}_k(t) - \tilde{a}_k^*(t)],$$

where $\mathbf{e}_k$ is a real polarization vector, and the sum over $k$ means the sum over the modes. $\mathbf{E}^{(+)}(\mathbf{r},t)$ and $\mathbf{E}^{(-)}(\mathbf{r},t)$ describe absorption and emission. The field related with absorption with different pathways is

$$\tilde{\mathbf{E}}^{(+)}(\mathbf{r},t) = K_1 \mathbf{E}^{(+)}(\mathbf{r}_1,t) + K_2 \mathbf{E}^{(+)}(\mathbf{r}_2,t)$$

The intensity of the light at the space-time point $x = (\mathbf{r}, t)$ is given by

$$I(x) = G^{(1)}(x,x) = \text{Tr} \left\{ \rho \mathbf{E}^{(+)}(x) \mathbf{E}^{(+)}(x) \right\},$$

where a density operator is $\rho = \sum_i P_i |i\rangle \langle i|$ and $P_i$ is the probability of $i$th state. The interfered intensity of the light with different pathways by itself is

$$I(\mathbf{r},t) = \text{Tr} \left\{ \rho \tilde{\mathbf{E}}^{(+)}(\mathbf{r},t) \tilde{\mathbf{E}}^{(+)}(\mathbf{r},t) \right\} = |K_1|^2 G^{(1)}(x_1,x_1) + |K_2|^2 G^{(1)}(x_2,x_2) + 2 \text{Re}[K_1^* K_2 G^{(1)}(x_1,x_2)],$$

where $G^{(1)}(x_1,x_2)$ is a general first-order correlation function. Using these notations, we can define the normalized first-order quantum coherence function as

$$g^{(1)}(x_1,x_2) = \frac{G^{(1)}(x_1,x_2)}{\sqrt{G^{(1)}(x_1,x_1)G^{(1)}(x_2,x_2)}}.$$
The first-order coherence function in classical and quantum theory can be interpreted as the expectation values in the correlation function of the fields. However, the first-order coherence function cannot tell about the states of light with identical spectral distributions but with quite different photon number distributions.

Hanbury Brown and Twiss suggested a new method to measure the correlation of intensities rather than fields for solving the problem of the first-order coherence function. As shown in Figure 1, the coincidence detection occurs only when detectors D1 and D2 register counts at the same time, and in classical theory, the rate of coincident counts is

\[ C(t, t + \tau) = \langle I(t)I(t+\tau) \rangle, \]  

where \( \tau \) is the time delay between two beams. Therefore, the classical second-order coherence function is defined as,

\[ \gamma^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau) \rangle}{\langle I(t) \rangle \langle I(t+\tau) \rangle} = \frac{\langle E^*(t)E(t)E^*(t+\tau)E(t+\tau) \rangle}{\langle E^*(t)E(t) \rangle \langle E^*(t+\tau)E(t+\tau) \rangle}. \]  

If we use a classical stable light beam, which means non-fluctuating intensity, the intensity is constant in time, therefore \( I(t) = I(t + \tau) = \bar{I}_0 \), and \( \gamma^{(2)}(\tau) = 1 \). However, the zero time-delay coherence function is not unity like the first-order coherence function. According to Cauchy’s inequality, \( \langle I(t) \rangle^2 \geq \langle I(t)^2 \rangle \) and thus

\[ 1 \leq \gamma^{(2)}(0) < \infty, \]  

For nonzero time delays, according to Cauchy-Schwarz inequality, we have
Thus, we can obtain the nonzero time-delay coherence function for a classical light.

$$\gamma^{(2)}(\tau) \leq 1, \text{ and } \gamma^{(2)}(\tau) \leq \gamma^{(2)}(0)$$

For all kinds of chaotic light, the second-order coherence function is related with the first-order coherence function as

$$\gamma^{(2)}(\tau) = 1 + \left| \gamma^{(1)}(\tau) \right|^2,$$

and since $0 \leq \left| \gamma^{(1)}(\tau) \right| \leq 1$, and $\left| \gamma^{(1)}(\tau) \right| = e^{-|\tau/\tau_0|}$ for large number of photons with Lorentzian spectra,

$$\gamma^{(2)}(\tau) = 1 + e^{-2|\tau/\tau_0|},$$

where $\tau_0$ is the coherence time of the source.

This effect is called the “photon bunching effect”, because as the delay goes to infinity, the second-order coherence function is 1, and with the zero-delay time, it becomes 2, which indicates the photons tend to come in bunches.

Here, we are interested in the second-order quantum coherence function for a single-mode field, defined as

$$g^{(2)}(\tau) = \frac{\langle \hat{E}^{(-)}(t)\hat{E}^{(-)}(t+\tau)\hat{E}^{(+)}(t+\tau)\hat{E}^{(+)}(t) \rangle}{\langle \hat{E}^{(-)}(t)\hat{E}^{(+)}(t) \rangle \langle \hat{E}^{(-)}(t+\tau)\hat{E}^{(+)}(t+\tau) \rangle}$$

$$= \frac{\langle \hat{a}^+\hat{a}^+\hat{a}\hat{a} \rangle}{\langle \hat{a}^+\hat{a} \rangle^2} = \frac{\langle \hat{n}(\hat{n}-1) \rangle}{\langle \hat{n} \rangle^2}$$

$$= 1 + \frac{\langle (\Delta \hat{n})^2 \rangle - \langle \hat{n} \rangle}{\langle \hat{n} \rangle^2}$$

This equation shows that the second-order quantum coherence function is independent on the delay time. We know that for thermal light $\langle (\Delta \hat{n})^2 \rangle = \langle \hat{n} \rangle + \langle \hat{n} \rangle^2$ and for coherent light, $\langle (\Delta \hat{n})^2 \rangle = \langle \hat{n} \rangle$. For those light, $g^{(2)}(\tau) \leq g^{(2)}(0)$. However, for the non-classical light, its statistics are sub-Poissonian, and thus $\langle (\Delta \hat{n})^2 \rangle < \langle \hat{n} \rangle$. Therefore, we have the following relation,

$$g^{(2)}(0) \leq g^{(2)}(\tau),$$

Since the above relation shows opposite property with the photon bunching, so it is called “photon antibunching” effect. This effect occurs when the photons arrive periodically in time and thus the coincidence rate in a time interval $\tau$ decreases. Therefore, we can determine how well a photon source has non-classical features measuring this antibunching effect.
III. Experimental Procedure

Samples were prepared by diluting dye molecules or quantum dots in solvent. We use clean Corning No. 1 microscope slide to apply sample solutions on it. The concentration of the solutions used is about 1nM. The solution of 50 μL is applied to slides using a spin coater, and the rotation speed is 3000 rpm for 30 seconds. In addition, PMMA hosts are mixed with sample solutions and coated on slides using the spin coater with same condition.

Furthermore, samples prepared in a liquid crystal host self-assembled in a chiral photonic bandgap structure are aligning using buffing and by shifting two substrates in the same direction relative to one another. By selecting proper concentration of chiral additive CB15 in nematic E7, we can choose transmission of such chiral photonic bandgap structures.

Samples were scanned using piezo-translation stage in conjunction with the confocal fluorescence microscope setup. Data collected at the APD’s was plotted using LabView-based software, and images were generated for each sample. Fluorescence was also observed using the CCD camera, which was used to save images and videos. In many of the images and videos collected, blinking, a phenomenon characteristic of single molecules or colloidal semiconductor quantum dots was observed. This data was used in conjunction with antibunching data generated by the TimeHarp card to demonstrate the presence of single emitters.

IV. Experimental Result and Analysis


Two kinds of samples, namely DiDye molecules and CdSe quantum dots, have been studied separately. A photo-counting CCD is first used to observe the 2-D fluorescence patterns dynamically. In this case, not only one can see the 2-D distribution of single emitters, but one can also see the blinking and bleaching of individual single emitters through a consecutive series of observation of the fluorescence on the same spot.

Fig. 2 shows the fluorescence image captured by the photon-counting CCD camera from DiDye molecules (concentration ~1nM) solution naturally dried on a microscope slip substrate. The background fluorescence and scattering of the slip substrate are shown on the right as a reference. One clearly sees from the figure the fluorescence from individual DiDye molecule.

From the attached video file (DiDye_500ms_gain255.avi), one can see the dynamical properties of the DiDye molecules, such as blinking, bleaching, etc. These properties are unique for single photon emitters, and therefore indicate that each bright spot seen in the CCD image is indeed emitted from a single dye molecule.

Since the alignment of the confocal microscope for capturing photon-counting CCD images are relatively easy as compared to the later procedures for Avalanche Photo Diode imaging, one always prefers to obtain such CCD images as a pre-alignment and sample area pre-selection for later confocal microscopy measurement.
Fig. 2 (a) Photon-counting CCD image of DiDye molecule single emitters; (b) photon-counting CCD image of substrate scattering and fluorescence as the background reference. (Accumulation time: 500ms; Gain: 255)

Fig. 3 (a) Photon-counting CCD image of 1 drop of DiDye + 3 drops of PMMA sputtered on the substrate; (b) photon-counting CCD image of 3 drops of PMMA sputtered on the substrate as the background reference. (Accumulation time: 500ms; Gain: 255)

The same measurement is carried out on the sample with DiDye molecule solution and PMMA solution sputtered on microscope slip. The PMMA can embed the dye molecules within its long-molecular structure and protect the dye molecule from the environment, and hence
improve the stability of DiDye emitters. Fig. 3 shows the fluorescence CCD images from the DiDye in PMMA (a) and from PMMA only (b).

![Fluorescence CCD images](image)

**Fig. 4 Photon-counting CCD image of CdSe QD sample (Accumulation time: 500ms; Gain: 255)**

Similarly, Fig. 4 shows the CCD image of fluorescence from CdSe QD samples (concentration ~ 1 nM). One should note that the fluorescence intensity of different QDs can vary in a wide range due to the quality of each QD. Despite of its multi-atom structure, QD has very similar fluorescence property as a single emitter, which means it also shows the properties of blinking and bleaching as one can sees from the attached video file (QD_1to10solution_500ms_255gain_movie.avi).

### 2. Study of fluorescence in a confocal microscopy set-up.

While the spatial resolution of the photon-counting CCD images is not too good, confocal microscopy can provide high resolution in both the transverse and longitudinal directions. Using nano-driving technique, the transverse distribution (image) of fluorescence from the samples can be obtained with a spatial resolution comparable to tens of nano-meters.

Fig. 5 shows the fluorescence image of pure DiDye molecules on the substrate in an area of 40×40 μm². One clearly sees the distribution of dye molecules over the area. Detailed fluorescence pattern from a single molecule is shown in Fig. 6. One should note that in Fig. 6(b), the molecule bleaches in the middle of the scanning, leaving only half of the fluorescence pattern. The bleaching supports the fact that the fluorescence pattern does comes from a single
emitter in stead of a collection of emitters. Meanwhile, one sees that the size of the fluorescence pattern from a single DiDye molecule is about 1.5 μm in diameter.

![Confocal micrograph of fluorescence from DiDye molecules (concentration: 1 nM) sample on a 40×40 μm2 area.](image)

**Fig. 5** Confocal micrograph of fluorescence from DiDye molecules (concentration: 1 nM) sample on a 40×40 μm2 area.

![Zoomed micrograph of fluorescence from a single DiDye molecule with scanning area size of (a) 10×10 μm2; (b) 2×2 μm2. Note that the molecule bleaches during the scan in (b) which gives only half of the fluorescence image.](image)

**Fig. 6** Zoomed micrograph of fluorescence from a single DiDye molecule with scanning area size of (a) 10×10 μm2; (b) 2×2 μm2. Note that the molecule bleaches during the scan in (b) which gives only half of the fluorescence image.

Fig. 7 shows the fluorescence image from a sample spin coated from 3 drops of DiDye solution and 1 drop of PMMA. In general, the average size of the fluorescence pattern from single molecule is larger than that from pure DiDye sample. For example, the single molecule fluorescence pattern shown in Fig. 7(b) has a diameter about 3 μm, almost twice the size of that in Fig. 6(b). This might due to the scattering of photons by PMMA molecule chains. Meanwhile,
the dye-molecule gets easily bleached for pure DiDye sample, but in a host of PMMA, the stability of the dye molecules are enhanced with less chance of bleaching.

Fig. 7 (a) Confocal micrograph of fluorescence from DiDye molecule on PMMA spin-coated sample on a 40×40 μm²; (b) Zoomed micrograph of fluorescence from a single DiDye molecule in the same sample with scanning area size of 4×4 μm².

Fig. 8 (a) Confocal micrograph of fluorescence from CdSe quantum dot sample on a 40×40 μm²; (b) Zoomed micrograph of fluorescence from a single CdSe QD in the same sample with scanning area size of 4×4 μm².

The same fluorescence patterns are measured and imaged for various CdSe quantum dots samples. The fluorescence patterns from pure CdSe quantum dots sample are shown in Fig. 8. Note that in the pattern of single CdSe QD fluorescence as in Fig. 8(b), the fluorescence intensity
revived from very low level (the lower half) to quite high level (the upper half), which is the blinking of a single emitter. Note also that the fluorescence patterns are elongated along the southwest-to-northeast directions, which might caused by the misalignment of the setup. Later after a re-alignment, we have much better spatial resolution (as one will see in the following graphics).

Fig. 9 (a) Confocal micrograph of fluorescence from CdSe quantum dot in CB15 liquid crystal host sample on a 40×40 μm²; (b) Zoomed micrograph of fluorescence from a single CdSe QD in the same sample with scanning area size of 4×4 μm².

Fig. 10 (a) Confocal micrograph of fluorescence from CdSe quantum dot in CLC4 liquid crystal host sample on a 40×40 μm²; (b) Zoomed micrograph of fluorescence from a single CdSe QD in the same sample with scanning area size of 2×2 μm².
Since liquid crystal is a very promising candidate for host to improve the performance of single emitters, we have tested the performance of CdSe quantum dots in two types of liquid crystal hosts. The first host is CB15 isotropic liquid crystal, which is somewhat opaque in room temperature. Fig. 9 shows the fluorescence patterns from CdSe QDs in such host. One can easily notice that the spatial resolution is much better in this case, and shows ring-shape patterns. The formation of this ring pattern could be the radiation pattern of the emitter, but it is also possible that the structure is an artifact caused by the confocal microscopy setup. Fig. 9(b) is a zoomed image which contains three QDs. Since there is no coherence among light emitted from different QDs, the ring patterns does not show interference as they overlap. One can also see some bright and dark horizontal stripes which comes from the blinking of the emitter.

Another liquid crystal host used is a cholesteric liquid crystal which is prepared by selection of proper concentration of chiral additive CB15 in nematic E7. CLC4 sample has a chiral photonic bandgap structure, and the center of the low-transmission band is around 579nm. It is expected that CLC4 host can increase the stability of CdSe QD emitters and it is also of interest to see how the photonic bandgap structure can influence the fluorescence life time of the emitters. Fig. 10 shows the fluorescence images of such sample, and one should note that in this sample, the fluorescence intensity really differs a lot among different QDs. The black strips in the single QD fluorescence pattern (see Fig. 10(b)) is a clear sign of single emitter blinking.


To quantitatively determine the fluorescence life time of quantum dot single emitters, the same confocal microscopy set-up is used together with a Time-Harp which is operating in a start-stop mode. The trigger-signal from the pump pulsed laser is used as the start channel, and the signal from one APD is used as the stop channel. Since the duration of the pump pulse is a few pico-seconds, very small as compared to the fluorescence life time (usually in the order of a few nano-second) of the CdSe QD single emitter, the correlation signal as a function of relative delay between the two channels shows exactly the time-dependent decay of the single emitters. Especially, when the decay shows a single exponential decay, we can calculate the spontaneous decay rate (Einstein’s A coefficient) using certain fitting algorithm.

First, the fluorescence life time of CdSe quantum dots samples with no host is measured. Fig. 11 shows a typical photon counts as a function of relative delay between the start and stop channels. The data is fitted with the following function

\[ N = N_{BG} + N_1 \exp(-t/\tau), \]

where \( \tau \) is the fluorescence life time of the emitter(s). The values of the measured fluorescence life time of CdSe QDs with no host are listed in Table 1. Different measurements on the same
quantum dots do show some consistency, but the variation of fluorescence life time among different quantum dots is relatively large, mainly due to the in-homogeneity of QDs sample.

![Fluorescence Life Time](image)

**Fig. 11** One fluorescence life time measurement of single CdSe dot with no host

| Table 1 Measured fluorescence lifetime of CdSe quantum dots without hosts (unit: ns) |
|----------------------------------|----------------------------------|----------------------------------|
|                                 | Data 1                          | Data 2                          | Average                        |
| Single QD #1                    | 0.8960                          | 0.9383                          | 0.9172                          |
| Single QD #2                    | 1.8526                          |                                 | 1.8526                          |
| Multiple QDs #1                 | 1.1080                          |                                 | 1.1080                          |
| Multiple QDs #1                 | 1.8300                          |                                 | 1.8300                          |

| Table 2 Fluorescence life time of CdSe QDs in different liquid crystal host 1 (unit: ns) |
|----------------------------------|----------------------------------|----------------------------------|
|                                 | Data 1                          | Data 2                          | Data 3                          | Average                        |
| 5CB, Area 1                      | 2.48734                         | 2.43839                         | 2.51072                         | 2.47882                         |
| 5CB, Area 2                      | 2.5761                          | 2.52411                         | 2.51526                         | 2.53849                         |
| CLC1, Area 1                     | 2.48403                         | 2.50745                         | 2.51487                         | 2.50212                         |
| CLC1, Area 2                     | 2.4937                          | 2.56224                         | 2.52553                         | 2.52716                         |
| CLC4, Area 1                     | 2.51839                         | 2.56719                         | 2.50071                         | 2.52876                         |
| CLC4, Area 2                     | 2.5997                          | 2.49586                         | 2.63179                         | 2.57578                         |
Table 2 shows the measured fluorescence lifetime of three different pre-prepared samples of CdSe QDs in three different liquid crystal hosts, namely 5CB, CLC#1 and CLC#4, respectively. The measurement data (also plotted in Fig. 12) shows that there is no obvious difference in the fluorescence lifetime of the QD in three different hosts.

Table 3 Fluorescence lifetime of CdSe QDs in different liquid crystal host II (unit: ns)

<table>
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<th>Data 1</th>
<th>Data 2</th>
<th>Data 3</th>
<th>Data 4</th>
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</table>

Fig. 12 Measured fluorescence lifetime for CdSe QDs in different hosts. Red and blue colors indicate the measurement of two different QD in the same sample.

Later on, three new samples (namely, CdSe QDs in CB15, CLC1 and CLC4 hosts, respectively) are prepared and measured again. The measured data are listed in Table 3 and plotted in Fig. 12. As one sees that the fluorescence lifetime of CdSe QDs in CLC4 host might
have longer fluorescence lifetime, but we need more measurement with the same sample before any conclusion can be made.

What we can conclude at this point is that the CdSe quantum dots have a single exponential decay rate with a fluorescence life time in the order of a few nano-seconds. The existence of liquid crystal hosts may have some influence on the fluorescence life time of the quantum dots, but the influence is not large. This may be due to the fact that the chiral photonic crystal band gap structure of our liquid crystal host are not sharp enough to modify the density of mode of the quantum dots.

4. Photon anti-bunching measurement

When photons are emitted one after another from a true single photon emitter, these photons have the unique property called “anti-bunching”. To observe this property, two APDs are placed after a polarization-insensitive beam splitter, and the correlation between the two signals are recorded as a function of interphoton time (relative delay between the two channels).

Fig. 13 shows a typical coincidence counts as a function of interphoton time with CdSe QDs in 5CB liquid crystal host. The repetition rate of the peaks is the same as that of the pump pulsed source, and the width of each peak are determined by the fluorescence lifetime of the emitter. The original data has many noises, contributed by quantum noise and the jitter of the APD, time harp, etc. To reduce the noise and improve the visual effect, we average the original data with a time window of 540ps (see the blue curve in Fig. 13). One could see that the height of the peak at zero interphoton time are slightly smaller than the height of peaks that on both sides. This is a sign of “antibunching”, but not too clean.

Fig. 14 and Fig. 15 show the result with CdSe QDs in CB15 liquid crystal host and CLC #4 host, respectively. In Fig. 14, there is no antibunching dip, indicating that the photons that come out of the sample does no longer hold the property of “one at a time”. In the sample of CdSe QDs in CLC host, however, the anitbunching dip is most obvious among the three kinds of samples. This is the first time that such property is experimentally observed, which shows that it is possible to use quantum dots in cholesteric liquid crystal host as an efficient room temperature single photon source.
Fig. 13 Histogram of coincidence counts of a single QD fluorescence in 5CB liquid crystal host under pulsed excitation.
There are a number of reasons to explain that cholesteric liquid crystal host can maintain the single photon property of quantum dot single emitters better than isotropic liquid crystal host. The main reason that isotropic host severely deteriorate the single photon property is scattering. Multi-trace scattering will smear out the sequence of emitted photons even from one single emitter, and hence reduce the antibunching property. In a cholesteric liquid crystal host, the chiral molecular structure forms a deterministic photonic band gap structure, which significantly modifies the density of modes of the sample. In such a host, the emitted photons can only be in a few modes with a deterministic polarization state, and therefore the chance of multi-path scattering is greatly reduced. Therefore, single photon sources based on quantum dots in CLC host are very promising for operating at room temperature and serve as “single photon on demand”.

Fig. 15 Histogram of coincidence counts of a single QD fluorescence in CLC #4 liquid crystal host under pulsed excitation which shows a dip at zero interphoton time, indicating antibunching.
V. Summary

In this experiment, we used confocal microscopy set up to observe the fluorescence of two kinds of single photon emitters, namely DiDye molecules and CdSe quantum dots in a variety of hosts (no host, PMMA, isotropic liquid crystal, cholesteric liquid crystal). Fluorescence lifetime and photon anti-bunching are observed and measured using a Time-Harp operating in a start-stop mode. Experimental data shows that liquid crystal host does not modify the fluorescence life time of quantum dot significantly if any. We have also observed photon antibunching from quantum dots in CLC host, which shows that such combination is a good room temperature single photon source.

VI. References