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Single-Mode-Fiber-Based Mach–Zehnder Interferometer Setup for Correlation Measurements for Single CdTe/ZnTe Quantum Dots

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We report on design and construction of a single-mode-fiber-based Mach–Zehnder interferometer system for measuring single photon indistinguishability from quantum dots emitting in visible spectrum (630±50 nm). The performance of the instrument was tested for its efficiency and usability in single-photon correlation measurements in a proposed experimental setup.

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1. Introduction

Semiconductor quantum dots (QDs) are still one of the main fields of study in the nanostructure solid state physics in the recent years. The localisation of exciton complexes within quantum dots results in a discrete luminescence spectrum. Each of individual emission lines corresponds to an excitonic complex with well defined number of carriers, which leads to non-classical character of the emitted light. Namely, the quantum dots were proven to produce a stream of photons characterized by sub-Poissonian statistics [1–3]. Another non-classical aspect of the light emitted by QDs is the indistinguishability of the emitted photons, which occurs due to relatively low exciton decoherence at low temperatures [4]. Photon indistinguishability was so far demonstrated experimentally for III–V quantum dots [5]. In contrast, experiments performed on II–VI QDs were limited to the issue of sub-Poissonian photon statistics [6]. In the meantime, the II–VI QD systems were brought to spotlight as a host for single transition metal dopants [7, 8]. For example, a single Mn^{2+} ion or Cr atom spin in a single CdTe/ZnTe QD was shown to undergo coherent evolution [9, 10], which is important from the point of view of quantum information processing. Progress in the solotronics urged us to explore the issue of photon indistiguishability in the II–VI system.

In this work we report on design and construction of the experimental setup for measurement of the photon indistiguishability in CdTe/ZnTe QDs. Such an experiment relies on measurement of the Hong–Ou–Mandel (HOM) interference between two different photons emitted by the quantum dot. Such effect occurs when two identical photons meet at the beamsplitter. Due to the interference, both photons have to leave the beamsplitter together, either at one or the other exit port [11]. The QD ensures that the emitted photons are identical with regard to the energy and the temporal profile, however the identical spatial mode needs to be assured by the experimental setup. The overlap of the spatial modes can be realized using single-mode optical fibers [5, 12]. In our design we followed this path and decided to construct a Mach–Zehnder interferometer based on single mode fibers, as shown in Fig. 1a. Such an element can be easily integrated into a detection path of a typical setup used in the single dot spectroscopy [13]. Feasibility of such integration is demonstrated in Fig. 1b, which features a photoluminescence spectrum of a single CdTe/ZnTe QD measured using a single-mode fiber in a setup based on the reflective Cassagrain-type microscope objective [14].

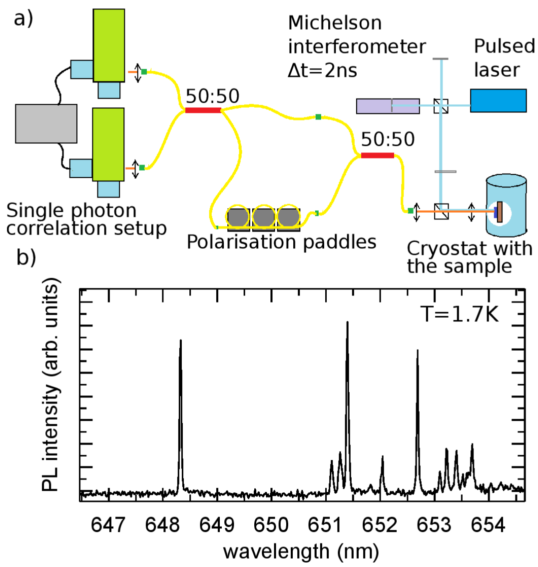

Fig. 1. (a) Schematic of the fiber-based interferometer setup. (b) Example of single QDs micro-PL spectrum measured in the fiber-based setup.

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2. Design of the interferometer

The emission range of CdTe/ZnTe spans from about 560 nm to 680 nm [15]. Particularly important from the point of view of single dot spectroscopy is the long wavelength end of this range. Correspondingly, in our setup we decided to use 630HP fiber (Thorlabs) with single-mode operation range 600–770 nm. The beam-splitters were realized as fused 50:50 single-mode couplers (TW630R5A2, Thorlabs). The constraint for the path length difference in the interferometer is given by two factors. On the one side, the path difference should be significantly longer than the typical exciton lifetime of 0.4 ns in CdTe/ZnTe QDs [6]. On the other side, the path difference should be shorter than one fifth of the laser repetition period (13 ns) in order to avoid overlapping of the peaks in the HOM correlations [5]. In our case we set the difference in the path length to 2.69 ns, which corresponds to 3 m of the fiber.

For the free-beam experiments, the Hong–Ou–Mandel effect is measured in a Mach–Zehnder type setup in which a polarisation-changing device has been implemented into one of the interferometer arms [11]. This element is even more important in fiber-based setup because of the need to cancel undesirable mismatch between the polarization state in both arms, which accumulate during propagation along the fibers. The implemented polarisation changing device is a manual fiber polarisation controller made out of three rotated paddles [16]. The number of loops in each paddle was chosen so that the middle paddle acts as a half-wave retarder while the other paddles acts as quarter-wave retarders with variable orientations.

Due to considerable time required to accumulate signal in photon correlation experiment [6], the HOM setup needs to be able to maintain the stable polarisation in both arms. Unfortunately, the fibers are highly susceptible to any mechanical manipulations or changes of temperature [17]. Therefore in order to preserve once set polarisation we employ an additional thermoisolator container for the interferometer in our setup. Such solution is fully passive and aims at reduction of the temperature noise from the laboratory air conditioning system. The performance of this solution was evaluated by measurement of the temperature variation inside and outside of our interferometer enclosure, as shown in Fig. 2.

Direct evaluation of the polarization stability of the interferometer was performed in a simple setup where we used laser pulses from optical parametric oscillator (OPO) pumped with a Ti:sapphire laser. The polarization of transmitted light was tested using a linear polarizer. The resulting signal was detected using a 1 GHz Si photodiode, which allowed us to monitor both arms of the interferometer simultaneously, as demonstrated in the inset in Fig. 3. During 12 h of experiment we did not observe a noticable change in the output polarization state, which proves the stability of the constructed setup.

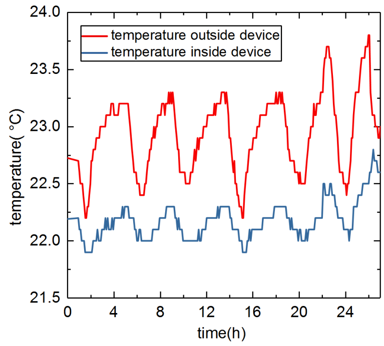

Fig. 2. Daily temperature measurements inside and outside of the interferometer device container showing the thermoisolator effect. The amplitude of the changes is reduced by factor of 3 with fully passive solution.

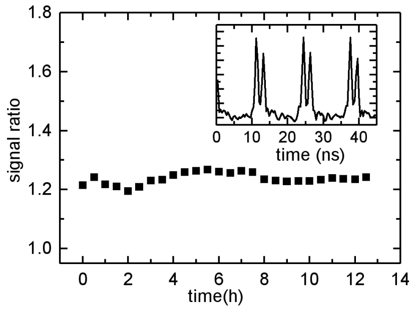

Fig. 3. The signal ratio from the interferometer arms in the time-resolved polarisation experiments. Inset: photodiode signal from interferometer arms after going through the polarisation measuring setup.

3. Analysis of the losses

The main losses in our interferometer device are caused by connections between single–mode fibers. To evaluate them we coupled a CW semiconductor 680 nm laser into the device and measured its power at the outputs in relation to its initial value. We calculated the insert loss and excess loss of the device. We found the value of insert loss to be < 6 dB with the differences between the outputs being < 0.3 dB. The excess loss of our setup was < 3 dB. In total the signal strength from both outputs was 49% of the input, which is close to a theoretical value of 54% obtained by the calculation taking into account the nominal losses on fiber–fiber connections and 50:50 fiber couplers.

4. Ideal-case results

Based on the experimental evaluation of the losses and non-equal splitting ratio in the interferometer we have performed a simulation of the expected results of photon correlation experiments. The result of this stochastic simulation is presented in Fig. 4. The calculation corresponds to the idealized scenario, in which the QD emits fully indistinguishable photons and only imperfections originate from the experimental setup, thus it can be considered a limiting case.

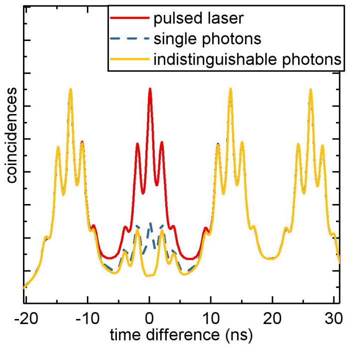

Fig. 4. Simulation of the expected result from the correlation experiment while using HOM setup for different nature of correlated photons. The simulation takes into account actual deviations from ideal splitting ratio in fiber beamsplitters and the finite resolution of the photon counters.

As seen in Fig. 4, all correlated photon pairs can be assigned to one of five bins, corresponding to different combinations of pathway of both photons in the interferometers. The HOM effect should manifest itself as a difference between the intensity of the central peak and the neighboring side-peaks. In the ideal case the central peak goes to nearly 0, but in the presence of pure dephasing it can be less pronounced [11]. We can estimate the expected sensitivity of the HOM experiment following a simple calculation. Assuming the count rate of r for each photodiode, the total number of counts in the first side peaks yields

$$N = \frac{2}{16} r \frac{r}{f_{rep}} t, \quad (1)$$

where f_{rep} is a repetition rate of the excitation laser and t is the accumulation time. The factor 2/16 approximates the ratio of the simulated intensity of the first side-peak to the total intensity of the 5-peak structure presented in Fig. 3. We evaluate this expression based on the realistic parameters from Ref. [6], where $r \approx 2000$, $f_{rep} = 76$ MHz, and $t = 8$ h. The reported count rates were corrected by a fiber coupling efficiency factor, which was tentatively selected to be 0.25. In result, we obtain prediction of $N = 190$, with in turn allows us to estimate relative uncertainity of the result as $1/\sqrt{N} \approx 0.072$.

5. Conclusions

From our measurements of the microluminescence, losses analysis and simulation of the expected results we conclude that our setup based on a single mode fiber-based Mach–Zehnder device should be capable of evaluating indistinguishability of photons emitted by a typical single CdTe/ZnTe QD with precision better than 8% for 8 h accumulation window.

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References

[1] C. Couteau, J.A. Gaj, R. Romestain, J.P. Poizat, *Appl. Phys. Lett.* **85**, 6251 (2004).

[2] C. Santori, M. Pelton, G. Solomon, Y. Dale, Y. Yamamoto, *Phys. Rev. Lett.* **86**, 1502 (2001).

[3] P. Michler, A. Kiraz, C. Becher, W.V. Schoenfeld, P.M. Petroff, L. Zhang, E. Hul, A. Imamoglu, *Science* **290**, 2282 (2000).

[4] A. Vagov, V.M. Axt, T. Kuhn, W. Langbein, P. Borri, U. Woggon, *Phys. Rev. B* **70**, 201305R (2004).

[5] C. Santori, D. Fattal, J.V. Caronkovic, G.S. Solomon, Y. Yamamoto, *Nature* **419**, 594 (2002).

[6] J. Suffczynski, T. Kazimierczuk, M. Goryca, B. Piechal, A. Trajnerowicz, K. Kowalik, P. Kossacki, A. Golnik, K.P. Korona, M. Nawrocki, J.A. Gaj, G. Karczewski, *Phys. Rev. B* **74**, 085319 (2006).

[7] J. Kobak, T. Smolenski, M. Goryca, M. Papaj, K. Gietka, A. Bogucki, M. Koperski, J.-G. Rousset, J. Suffczynski, E. Janik, M. Nawrocki, A. Golnik, P. Kossacki, W. Pacuski, *Nat. Commun.* **5**, 3191 (2014).

[8] T. Smolenski, T. Kazimierczuk, J. Kobak, M. Goryca, A. Golnik, P. Kossacki, W. Pacuski, *Nat. Commun.* **7**, 10484 (2016).

[9] M. Goryca, T. Kazimierczuk, M. Nawrocki, A. Golnik, J. Gaj, P. Kossacki, P. Wojnar, G. Karczewski, *Phys. Rev. Lett.* **103**, 087401 (2009).

[10] A. Lafuente-Sampietro, H. Utsumi, H. Boukari, S. Kuroda, L. Besombes, *Appl. Phys. Lett.* **109**, 053103 (2016).

[11] C.K. Hong, Z.Y. Ou, L. Mandel, *Phys. Rev. Lett.* **59**, 2044 (1987).

[12] M. Gschrey, A. Thoma, P. Schnauber, M. Seifried, R. Schmidt, B. Wohlfeil, L. Kruger, J.-H. Schulze, T. Heindel, S. Burger, F. Schmidt, A. Strittmatter, S. Rodt, S. Reitzenstein, *Nat. Commun.* **6**, 7662 (2015).

[13] T. Kazimierczuk, M. Goryca, M. Koperski, A. Golnik, J.A. Gaj, M. Nawrocki, P. Wojnar, P. Kossacki, *Phys. Rev. B* **81**, 155313 (2010).

[14] J. Jasny, J. Sepiol, T. Irngartinger, M. Traber, A. Renn, U.P. Wild, *Rev. Sci. Instrum.* **67**, 1425 (1996).

[15] P. Wojnar, C. Bougerol, E. Bellet-Amalric, L. Besombes, H. Mariette, H. Boukari, *J. Cryst. Growth* **335**, 28 (2011).

[16] E. Collett, *Polarized Light — Fundamentals and Applications*, Marcel Dekker, New York 1993.

[17] S. Rashleigh, *J. Lightwave Technol.* **1**, 312 (1983).