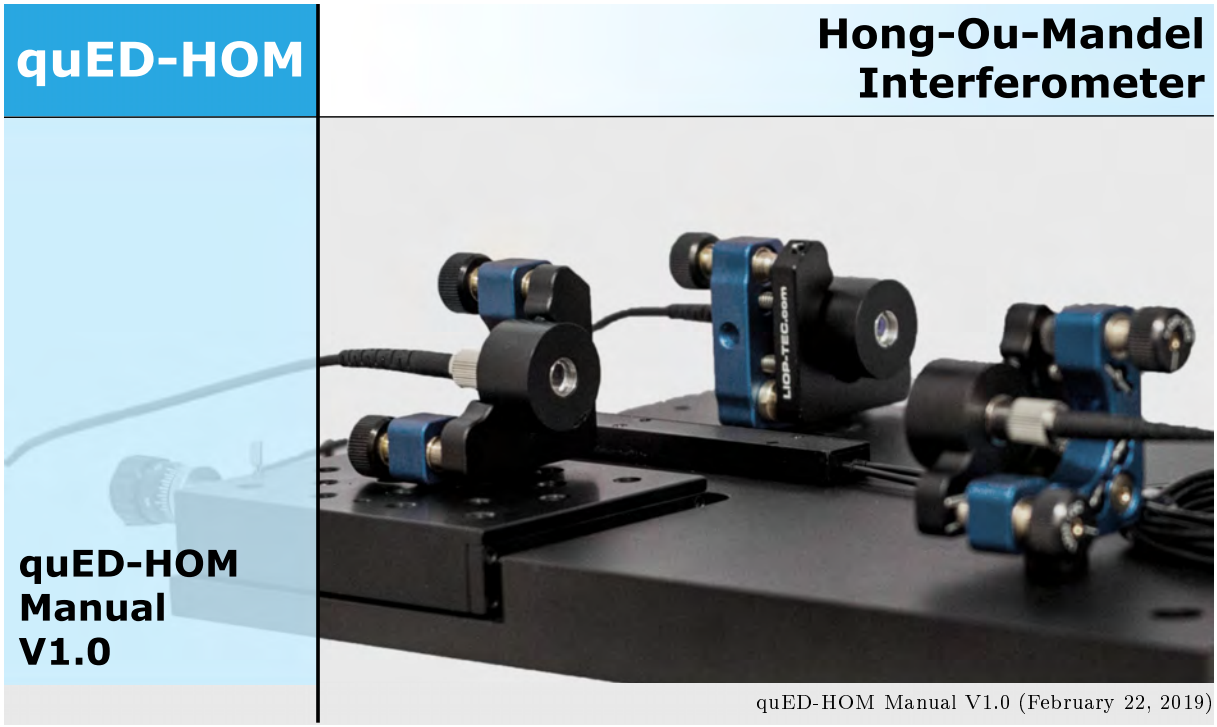

Contents

1 quED-HOM: Hong-Ou-Mandel Interferometer Manual

1.1 Quickstart Manual

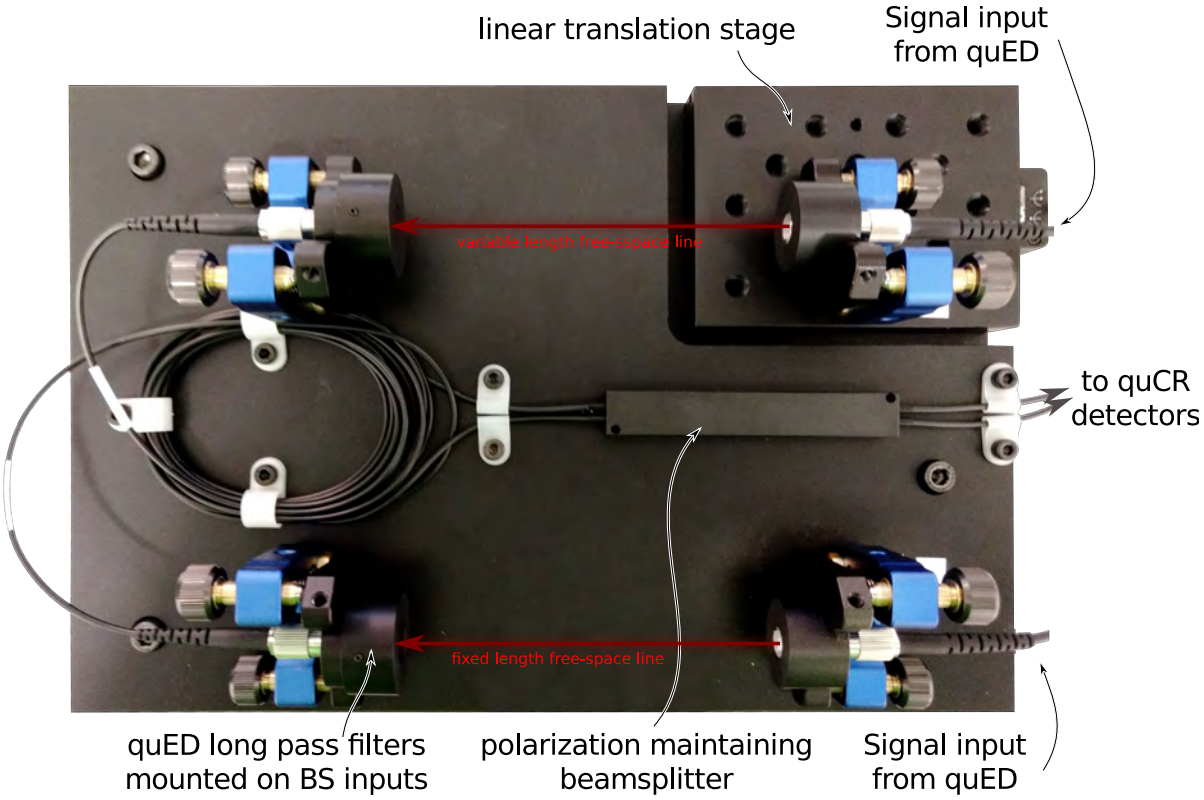

Figure 1.1: The quED-HOM setup

The quED-HOM consists of two free space lines, each between two fiber couplers and one of them variable in length, and one fiber coupled beam splitter. If the Add-On has been matched to your quED by qutools, all you have to do is (see Fig. 1.2)

- Connect the output fibers of the quED to the respective input fibers with a fiber connector.
- Make sure *quED out 1* is connected to *HOM in 1* and also fibers *2*.
- Connect both output fibers to the double detector module in the quCR.

- Remove the half wave plate from the quED source and turn up the laser of the quED to operating current.
- Block one of the free space lines and check the measured single count rates. Optimize the coupling by carefully tuning both adjustment screws of the mirror holder on one side of the unblocked free space line. The single counts rates should be approximately at 25000-30000 counts per second in both detectors.
- Repeat with the other free space line.
- With both lines unblocked, you should measure between 1000 and 2000 coincidences per second.
- With that, you can proceed to do the actual experiment 2.1 Hong-Ou-Mandel Dip

Otherwise, please refer to 1.5 Preparatory Steps and 1.6 Alignment and Operation.

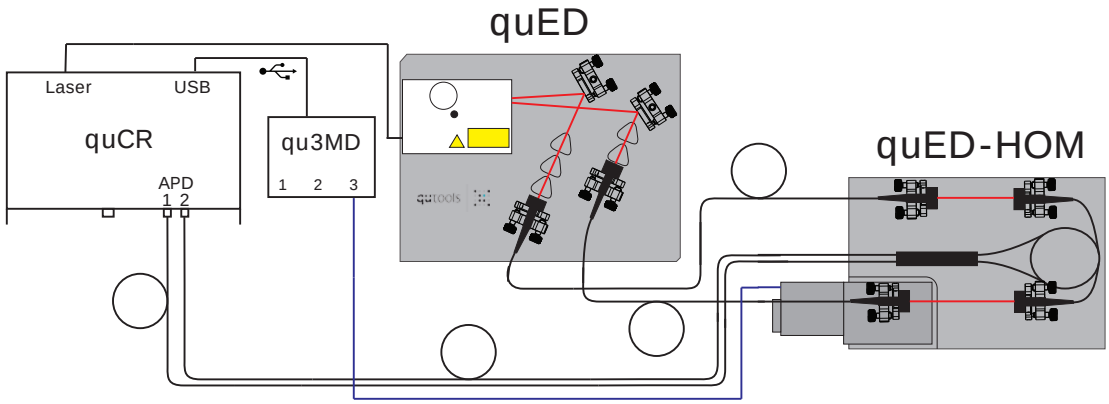

Figure 1.2: Schematic setup of the quED-HOM Add-On

1.2 Introduction

The quED-HOM is a two-photon interferometer designed to operate together with the qutools quED 'Entanglement Demonstrator' or any other fiber-coupled source of time-correlated photon pairs at the wavelength band around 810 nm. It is an education-oriented experimental module capable of demonstrating a quintessential quantum mechanical phenomenon – the interference of two indistinguishable photons at a non-polarizing beam-splitter. This phenomenon is often called Hong-Ou-Mandel interference.

The simplicity of the experimental arrangement and the clarity in the underlying physics make the experiment well suited for practical demonstrations in student lab courses.The experimental sign of the two-photon interference – the V-shaped drop or the 'dip' in the number of detected photon pairs towards zero - provides a measure of the time separation between the photon arrivals with femtosecond precision. Moreover, the depth of the dip is directly related to the degree of indistinguishability of the two photons.

The interferometer is fiber-based and manually driven. At its heart there is the polarization-maintaining fiber coupler ensuring high spatial and polarization overlap of the interfering photons. The all-fiber solution ensures not only a high quantum-interference visibility, but also greatly simplifies the search and alignment procedures.

To record the interference dip, the path difference between the interferometer arms has to be scanned in micrometer-resolved steps. This is accomplished using the integrated manual translation stage equipped with a differential micrometer screw (or the high precision stepper motor if you have the motorized version).

1.3 Basic Principles of Operation

The quED-HOM is not an interferometer in the traditional sense, i.e. the light is not first split and later recombined like in standard Michelson or Mach-Zehnder interferometers. Rather the time-correlated photons provided by a photon-pair source enter the two input ports of the balanced beam-splitter. In the quED-HOM, the fused 50:50 polarization maintaining fiber coupler is used as the beam splitter. This all-fiber solution ensures a good spatial mode overlap of the interfering photons, and, provided that the linear polarization with correct orientation is launched into the input fibers of the coupler, also a good polarization-mode overlap of the photons. The latter is ensured due to the use of polarization-maintaining fibers, which preserve the linear-polarization of the light that is launched into the fibers. Moreover, the coupler is designed such that for linear polarization, which is maintained in the fibers, the splitting ratio is very close to the ideal 50:50 at the operating wavelength.

Either arm of the two-photon interferometer contains a short free-space optical line, i.e. the fiber-coupled photons coming from the source are collimated using a lens and after a short free-space transmission collected again into the input fibers of the coupler. One of the lines has a variable length, which makes the tuning of the path difference between the two arms possible. The tuning is controlled by the manual or motorized translation stage. This enables the required micrometer-resolved steps for achieving the precise time overlap of the photons and scanning through the interference dip.

1.4 Description

This section shows the individual optical components of the quED-HOM. The description follows the notation shown in the photo of the interferometer module in Fig. 1.1.

All the components of the quED-HOM are mounted on a solid aluminum base plate. The four kinematic mirror mounts with adjustable-focus collimators build up the two free-space lines; one of the lines has a variable length, whereas the length of the other is fixed. All the fiber collimators are FC/PC compatible and contain aspheric lenses with adjustable focus. The focus can be adjusted by rotating the aspheric lens in the aluminium housing

of the collimator. This should never become necessary and a special tool is required. The four collimators are pre-aligned for maximum fiber-to-fiber transmission. Moreover, their axial rotation is carefully adjusted for the fiber axis to match.

The setup is equipped with an extra pair of fibers attached to the quED-HOM input ports ("Signal input from quED" in fig. 1.1). These should not be detached. Thus the polarization maintaining fibers from the quED are to be connected to these fibers using the provided fiber mating sleeves. All fibers are labeled to ensure that each of the quED fibers is always connected to the same quED-HOM fiber. If they are mixed up, the position of the Hong-Ou-Mandel interference in the linear translation stage changes and it is difficult to find it again.

The output polarization maintaining fibers of the coupler are connected to the read-out unit of the quED during operation.

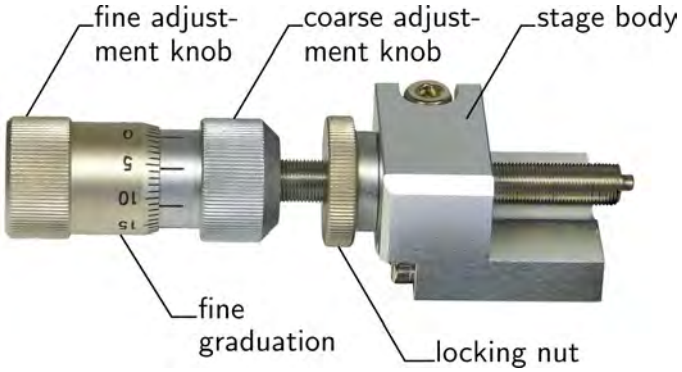

Figure 1.3: The differential micrometer with two knobs for coarse and fine adjustment.

1.5 Preparatory Steps

Upon receipt of the quED-HOM, please verify carefully that all the mechanical and optical parts of the module are free of any damage. If this is not the case, please contact qutools immediately; the contact details are given at the end of the manual. If no damages are found, please proceed according to the following steps:

1. The interferometer module is fastened to the box with three screws. Optionally remove the screws from the top and gently remove module from the box. Put it next to the photon-pair source and the control/read-out unit.
2. Before making any connections of the interferometer module to the source and the controller, please verify first that the source delivers a steady stream of photon pairs with pre-defined polarization. To this end, please:
   a) Remove the half-wave plate from the quED pump assembly (under the white circular cap). Thereby, only photon pairs of one polarization are generated as needed.

b) Remove the polarizers from the quED.

c) Readjust the collection of photons carefully with the adjuster knobs of the fiber coupler mounts only for a maximum number of coincidences.

3. Unplug the connectors of the single mode fibers from the control unit and insert them into the mating sleeves at the quED-HOM input fibers. Please respect the labeling to find the matching fiber pairs. Gently fasten the connectors in the FC/PC receptacles of the collimators.
4. To connect the quED-HOM to the control unit, please plug the output polarization-maintaining fibers of the fiber coupler into the optical inputs of the control unit. On completion of this step, the interferometer module is prepared for the operation.

1.6 Alignment and Operation

Due to the use of polarization maintaining fibers in the quED and a polarization maintaining fiber coupler for the photon overlap the whole alignment procedure of the quED-HOM is fairly simple. The user only has to realign the fiber-to-fiber coupling in both free-space lines for maximum coupling.

1. Make sure the preparatory steps from the previous section have been carried out, especially item 2.
2. Block both free-space links with a screen and register the displayed idle single-count rates. They should be close to dark count rates of detectors. If significantly higher count rates are observed, the appropriate measures have to be taken, e.g. the level of stray light in the room has to be lowered.
3. Choose the free-space line to be aligned first and unblock it.
4. The displayed single-count rates in both channels should increase above the idle single-count rates after unblocking the coupling. When correctly aligned, the aggregate number of detected photons in both channels should reach about 50 % of the single-count rate measured directly in the corresponding arm of the source. If this is not the case, the fiber-to-fiber coupling is misaligned and it has to be readjusted. Please choose one of the following possibilities and act accordingly:

   a) If the displayed single-count rates reach the level specified above, please proceed to the step 5.

   b) If the displayed single-count rates increased, but did not reach the level specified above, please try improving the fiber-to-fiber coupling according to the description given in section 1.6.1.

   c) If the displayed single-count rates in both channels did not change after unblocking the free-space line please try finding the signal by angle tuning the receiving collimator. With this aim, please scan angles in a systematic way around the initial position (which should be always remembered), while observing single-count rates at the control unit. As the scanning is performed

blindly without any reference, the success comes only if the initial misalignment is small. If the scanning fails and single-count rates do not raise above the level of idle counts, please follow the alignment steps given in section 1.6.3.

5. After adjusting the fiber-to-fiber coupling the same procedure starting from the step 3 should be repeated for the second free-space line. The free-space line, which has already been adjusted should be blocked now.

After aligning both free-space lines the search for the interference dip can begin. For more information on how to proceed with the search we refer to the section 1.6.2.

1.6.1 Improving the Fiber-to-fiber Coupling

The alignment of coupling in the given free-space line of the interferometer is performed by angle-tuning the transmitting and receiving collimator. The angular movements are controlled using a pair of fine-thread screws on the kinematic mirror mounts. One of the adjustment screws provides the control in the vertical and the other in the horizontal direction.

The adjustments of the transmitting and receiving collimator are coupled - each adjustment of the transmitting collimator has to be accompanied by a corresponding adjustment of the receiving collimator. For example, if you tilt the transmitting collimator in the horizontal direction and the count rates drop, the receiving collimator has to be tilted in the horizontal direction as well, such that the single count rates reach their maximum again. This "angular walking" of the collimators has to be iteratively performed in both horizontal and vertical directions. If done properly the angular setting with the maximum observed single-count rates is found after a while.

Alignment steps have to be sufficiently small to avoid complete loss of the photon-coupling. For example, if you tilt the transmitting collimator, allow the count rates to drop not more than to a quarter of their initial values and then compensate for this drop by an appropriate movement of the receiving collimator. As mentioned in the section 1.4 the focuses of the collimators are pre-aligned for maximum fiber-to-fiber transmission at the operating wavelength of 810 nm. If a strong doubt for a correct alignment arises, the focus might be changed by rotating the aspheric lens in the collimator housing using a spanner wrench. Due to a high positioning sensitivity of the aspheric lens in the collimator, the adjustment steps must be relatively small - in the order of a few degrees only! Please note that every adjustment leads to a misalignment of fibre-to-fibre coupling and that has to be corrected. The aspheric lens should be adjusted to the position corresponding to the highest detected single-count rates. coupling adjustments are unclear, it may be useful to examine the movements of the coupling mode with a visible light provided by an auxiliary laser (e.g. fiber checker module delivered with the quED). Please refer to the instructions in section 1.6 on how to properly make the coupling modes visible. Please be aware of the fact that any adjustments of the coupling without monitoring of the count rates might lead to a misalignment of the interferometer! Therefore remember the initial positions of the adjustment screws and go back when finished.

1.6.2 Searching for the Interference Dip

The search of the interference dip is performed by changing the length of the free-space line using the linear translation stage and observing changes in the measured coincidence count rate. As soon as a significant drop in the coincidence count rate is observed, the two interferometer arms are adjusted to have the same length and the interference dip is found. Please note that the detected coincidence count rate C always fluctuates about its mean value $\bar{C}$ with a Poisson standard deviation given by $\sigma_C = \sqrt{C}$. The interference should manifest itself by the drop of coincidence count rate deeply below the Poisson noise. If the input polarization state to the polarization maintaining fiber coupler is correctly aligned, the coincidence count rate should decrease to at least half of the value $\bar{C}$ outside the interference dip.

The scanning of the translation stage is controlled with the coarse adjustment knob on the differential micrometer screw. The knob is normally secured using the locking nut, and has to be loosened before usage. The scanning step angle should be chosen according to the expected width of the interference pattern. This width is inversely proportional to the spectral bandwidth of photons. The Hong-Ou-Mandel dip width should be expected to be only ≈ 8 μm. Given the resolution of the coarse adjustment screw of 500 μm per revolution, the scanning step angle should be restricted to no more than 5° in such a case.

Due to the coarse-adjustment travel range of 25 mm, the path-length difference of the interferometer arms can be scanned in the limited range of [-2.5, 22.5] mm, see also section 1.4. If the interference pattern is not located within the range, the single mode fibers from the source have to be switched first; i.e. the fiber connected to the variable-length free-space line is to be plugged into the transmitting collimator of the fixed-length line and vice versa. To accomplish the scanning with the switched fibers the alignment procedure described in section 1.6 has to be repeated.

The quED is designed to deliver the photon pairs with the mutual path delay of about 10 mm. Therefore, the basic scanning range should be large enough to cover the position of the interference pattern. Rarely it might however happen that the single-mode fibers connecting the quED with the quED-HOM have significantly different length, rendering the basic scanning range insufficient. In such a case, the scanning range must be extended by shifting the variable-angle mount with the transmitting collimator in the fixed-length free-space line. For this purpose, two additional taps for securing the mount are provided in the base plate. The taps are separated by 20 mm, allowing thus to enlarge the path-length difference range to [17.5, 42.5] mm and [37.5, 67.5] mm, respectively. To shift the variable-angle mount, please:

1. Unplug the single-mode fiber from the transmitting collimator.
2. Loosen and retract the hex socket screw attaching the mount to the base plate.
3. Shift the mount so that the mounting hole and the respective tap are flush. Orient the mount such that the transmitting collimator points towards the receiving collimator. Tighten the hex socket screw to hold the mount firmly in place.

4. The fiber-to-fiber coupling can be aligned now according to the procedure given in section 1.6.3. Afterwards the search of the interference dip can be repeated.

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1.6.3 Restoring Fiber-to-fiber Coupling

After transport or after changing the distance between the collimators in the fixed-length free-space line, the fiber-to-fiber coupling can be lost completely. To restore the coupling, please proceed according to the following steps:

1. Disconnect one single-mode fiber from the twin detection module (always use protective caps to cover fiber connectors and input optical receptacles).
2. Disconnect the fiber of the transmitting collimator from the fiber mating sleeve leading to the quED.
3. Connect the fiber checker (delivered with the quED) to the now free end of the fiber and switch it on (long press the button on the side, then short press to activate the continuous mode). The red laser beam coming from the transmitting collimator is now visible.
4. Locate the position of the laser beam on the receiving collimator. Align the angular pointing of the transmitting collimator using the two adjustment screws on the kinematic mount such that the laser beam hits the center of the aspheric lens in the receiving collimator.
5. This step aims to align the receiving collimator. It can be omitted if the fiber-to-fiber coupling has been lost because of shifting the transmitting collimator in the fixed-length line (the receiving collimator should have stayed aligned). Switch off the fiber checker, unplug it and connect it to one of the output fibers of the polarization maintaining fiber coupler. The red laser beam coming from the receiving collimator and propagating towards the lens in the transmitting collimator is now visible. If aligned correctly, the beam should hit the center of lens. Please correct the angular pointing of the receiving collimator using the two adjustment screws on the kinematic mount if necessary.
6. If aligned correctly, the red laser light coming from the transmitting collimator should be partly coupled into the input single mode fiber of the polarization maintaining fiber coupler. To check this, remove the protective cap from one of the output single mode fibers and put a piece of blank paper in front of the fiber tip. The faint red spot should be clearly visible. Never look into the fiber directly! Permanent eye damage could result!
7. Adjust the transmitting collimator for maximal brightness of the spot.
8. Switch off the fiber checker, unplug it and connect the output polarization-maintaining fibers of the fiber coupler into the optical inputs of the twin detection module. Reconnect the single-mode fiber from the quED to the transmitting collimator.

Upon completing the last step, the procedures of sections 1.6 and 1.6.2 should be followed again to align the quED-HOM and observe the interference pattern.

2 Experiments with the quED-HOM

2.1 Hong-Ou-Mandel Dip

When two *indistinguishable* photons impinge on both inputs of a beam splitter *simultaneous*, the will leave the beam splitter together. Where does this weird behaviour without classical analogy come from? What does *indistinguishable* and *simultaneous* mean exactly? This experiment yields answers.

2.1.1 Theoretical Background

For the single photon impinging on a balanced non-polarizing beam-splitter there is an equal chance of being reflected or transmitted. If two photon-counting detectors are positioned at the output ports of the beam-splitter, the photon is registered at one or the other detector with equal probability, but never in coincidence at both detectors. The

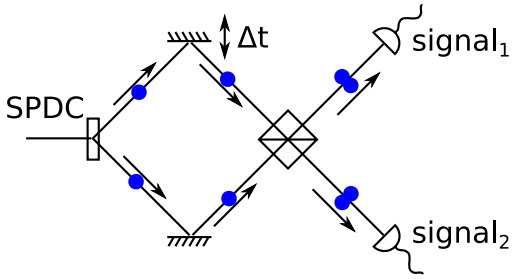

Figure 2.1: If the two photons impinging on the beam splitter are indistinguishable in all degrees of freedom, then they will always depart on the same side.

observed perfect anti-correlations between the detection events provide a simple experimental test of the photon indivisibility. In the experimental scenario with the two photons simultaneously entering the input ports of the beam-splitter, one would expect the four possibilities for the output: both are transmitted (Fig. 2.2a), both are reflected (Fig. 2.2b), and one is transmitted while the another reflected (Fig. 2.2c and Fig. 2.2d).

The detectors at the beam-splitter outputs should thus register half of the photons in coincidence while the other half is not detected. This intuitive explanation however fails to account for two-photon interference, which occurs if the two photons are indistinguishable in all degrees of freedom, i.e. the photons have the same wavelength, polarization and spatio-temporal mode. In such a case the first two possibilities – when both photons are transmitted (Fig. 2.2a) or reflected (Fig. 2.2b) – cannot be distinguished from one another because there is always one photon in either output mode. As a result, the two possibilities are coherently superposed. Due to unitarity of the beam-splitter transformation there is always an overall π-phase shift between the two possibilities and therefore they completely cancel each other. The involved π-phase shift is universal and independent of a specific beam-splitter and therefore the described destructive interference appears for any practical realization.

For the other two possibilities left [(Fig. 2.2c and Fig. 2.2d)], the photons always exit the same output port of the beam-splitter. This will manifests itself in the absence of the coincidence counts. By scanning the relative time delay between the photon arrivals at the beam-splitter, the degree of temporal distinguishability of the two photons is effectively changed, and therefore the dip in the coincidence count rate can be observed. For zero delay, the perfect photon overlap in the time domain is ensured, and the coincidence rate should theoretically drop to zero. This is however never the case in practice because of experimental imperfections such as the the deviation from the ideal 50:50 beam-splitter splitting ratio, imperfect spatial-mode or polarization-mode overlap. Therefore the dip with a limited visibility is always recorded experimentally. The measured visibility corrected for the imperfect splitting ratio gives a direct measure of indistinguishability of the input photons.

Unlike the interference effects in conventional Mach-Zehnder or Michelson interferome-

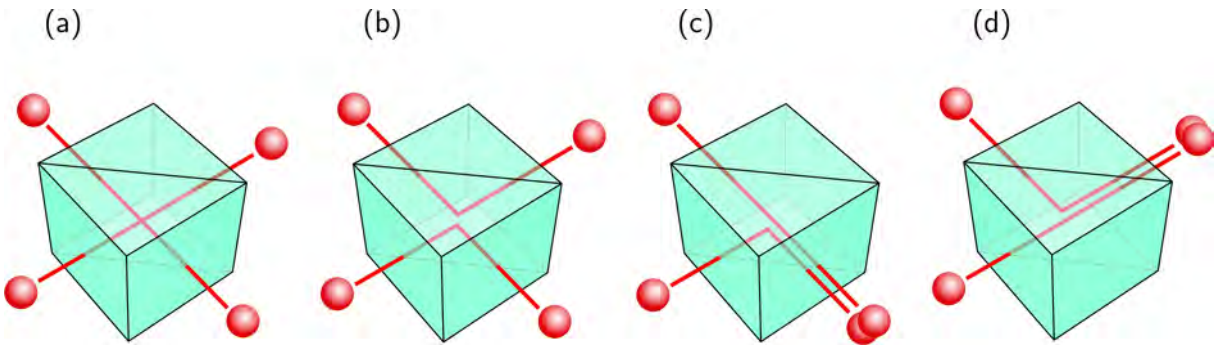

Figure 2.2: Four alternative paths for the passage of two photons through balanced non-polarizing beam-splitter.

ters, the Hong-Ou-Mandel effect does not require the phase stability of the interferometer arms. The path differences of the arms need not be kept constant to within a fraction of wavelength, but only to within a fraction of the photon coherence length. From a practical point of view the Hong-Ou-Mandel effect can be viewed as a method to gauge the femtosecond time intervals (corresponding to micrometer length scales) between the photons and by implication the length of the photon wave packets. It is relatively straightforward to calculate the coherence length of the photon wave packets from the measured interference dip.

2.1.2 Realization with the quED

Necessary Components

- quED setup with quCR
- quED-HOM Hong-Ou-Mandel Add-On

Experimental description

Setup As in Fig. 2.3, the output fibers of the quED are connected to the inputs of the quED-HOM. The outputs of the Add-On are connected to the detectors of the control and readout unit quCR. In the motorized version, the motor driver qu3MD has to be connected via USB to the quCR, the motor itself plugged in to site 3 of the qu3MD. The AddOn should be pre-aligned as described in the manual.

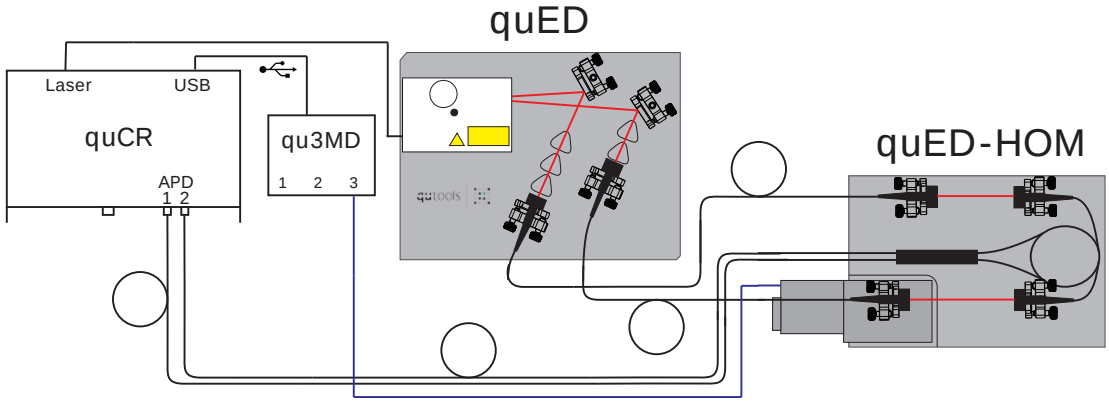

Figure 2.3: Setup of the Hong-Ou-Mandel experiment with the quED.

Searching for the Interference Dip

The search of the interference dip is performed by changing the length of the free-space line using the linear translation stage and observing changes in the measured coincidence count rate. As soon as a significant drop in the coincidence count rate is observed, the two interferometer arms are adjusted to have the same length and the interference dip is

found. Please note that the detected coincidence count rate C always fluctuates about its mean value $\bar{C}$ with a Poisson standard deviation given by $\sigma_C = \sqrt{C}$. The interference should manifest itself by the drop of coincidence count rate deeply below the Poisson noise. If the input polarization state to the polarization maintaining fiber coupler is correctly aligned, the coincidence count rate should decrease to at least half of the value $\bar{C}$ outside the interference dip.

With the motorized version, the linear translation stage is controlled by the quCR. For this, the "'linear scanning"' Tab is used. Because of the natural spectral width of the photons, the Hong-Ou-Mandel Dip is only $\approx 8\,\mu$m wide, the step size should therefore not exceed $3-5\,\mu$m for a first coarse search, see also Tab. 2.1. The approximate position of the dip is marked by the cut adhesive strip. In the manual version, the position of the coarse adjustment screw is also marked. The white area must be on top while the fine adjustment screw has to be set to the 0 position. For a coarse search, the micrometer screw with $500\,\mu$m linear distance per revolution should not be moved by more than about 5° per step.

A neat measurement run for analysis of the Dip can be done using the values in Tab. 2.2.

Table 2.1: The settings for coarse searching of the HOM-Dip.

chan	stage	Stepsize	Target	Integration
(12)	OWIS	8/9600	±2 mm	0.1 s

Table 2.2: The settings for a good measurement run. Before the measurement, set the motor to a position away from the interference; the target is then accordingly chosen on the opposite side.

chan	stage	Stepsize	Integration
(12)	OWIS	1/9600	1 s

Measurement example

2.1.3 Didactic Material

1. What does the reduction in coincidence counts at equal path lengths mean?
2. How could one verify this hypothesis in a continuative experiment?
3. What impact does an altered splitting ratio of the beam splitter have on the results? Calculate the depth of the minimum for a ratio of 40% to 60%.
4. The single photons of the quED have a very broad bandwidth ($\Delta\lambda \approx 30\,$nm). Since the pump laser spectrum is narrow and energy conservation must hold, the

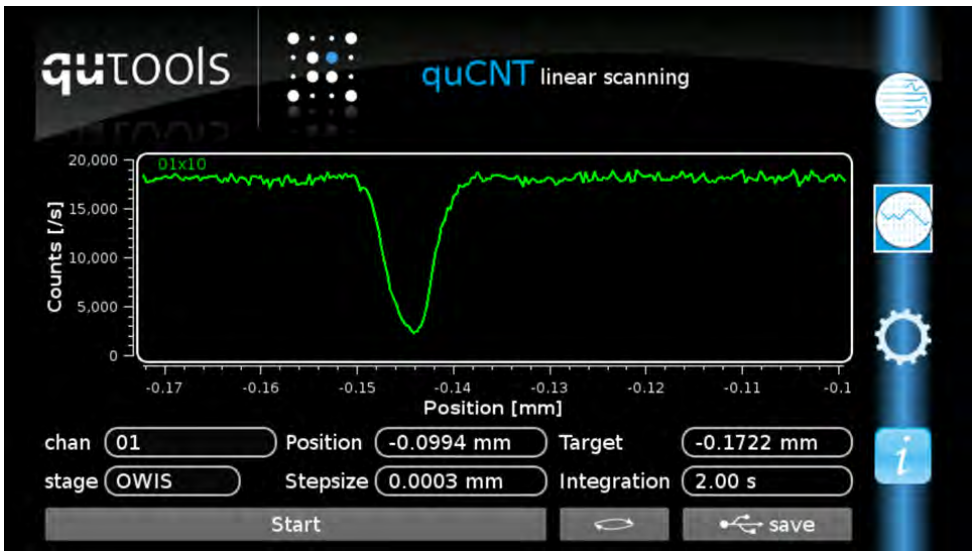

Figure 2.4: Der Dip in der Koinzidenzzählrate offenbart sich bei gleichzeitigem Auftreffen der Photonen auf dem Strahlteiler.

wavelengths of the two photons of one pair are correlated, such that they will differ greatly (frequencies must be symmetrical around $c/810\,\mathrm{nm}$). With that, the two photons are very well distinguishable and should not interfere at the beam splitter, contributing to the HOM-Dip. Why do we measure such a good contrast regardless?

2.1.4 Sample Solution

For the sample solution please refer to the qutools quED-HOM page `http://qutools.com/quED-HOM`.