Reducing handling errors on a Mach Zehnder interferometer and illustrating single photon interference

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At Vetenskapens Hus there is an exhibition where single photon interference is demonstrated for younger students, using a Mach Zehnder interferometer, to arouse their interest in physics. This report describes the work done to improve the interferometer for this exhibition by making it user-friendly, less exposed to the risk of handler errors and to create a more interesting experience for the students. In order to accomplish this, custom electronics were made by hand and a user interface was created using LabView. Also, a manual was prepared for the staff at Vetenskapens Hus with instructions of how to work the components of the system and how to align the interferometer correctly.
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1 Introduction

One of the most notable concepts in quantum mechanics is the concept of wave-particle duality. When Einstein introduced the photon as a concept to describe the photoelectric effect [1], the older debate about the nature of light took another turn and one of the most well known experiments showing the wave and particle properties of light is Young’s double-slit experiment [1], which shows that interference patterns are obtained even when single photons are sent through the slits.

However, in this thesis we are focusing on another experiment, using an Mach Zehnder interferometer (Will hereafter be referred to as MZI). The MZI is used in a set-up at Vetenskapens Hus demonstrating the concept of wave-particle duality for younger students to arouse their interest in physics. Vetenskapens Hus was founded cooperatively between KTH and Stockholms Universitet to create a place where younger students get a hands-on experience of natural sciences.

This thesis describes the work to improve the MZI set-up at Vetenskapens Hus by making it easier and safer to handle, and to illustrate the interference in more detail.
2 Theory

This chapter provides an introduction to the MZI and theory, to understand what the exhibition at Vetenskapsen Hus is all about. The last section of this chapter is about electronics. Ohm’s law and the circuit symbols of some electrical components are presented to make it easier to understand following chapters.

2.1 The Mach Zehnder Interferometer

The Mach Zehnder interferometer usually consists of two beam splitters and two mirrors. A laser beam entering this system will split into two beams at the first beamsplitter. Later on, after the beams getting reflected by the mirrors, they will meet again at the second beam splitter to superpose and produce interference patterns. This happens because of the relative phase \( \phi \) of the superposed electromagnetic waves.

If the total phase shift difference between the electromagnetic waves entering detector B will equal to \( \pi \), the amplitudes of those waves will cancel out and this is what we know as destructive interference [2]. On the other hand, the relative phase shift of the beams reaching A is zero, which results in constructive interference. In this interferometer a phase shifter is added, which makes it possible to change at which detector the destructive interference will occur.

![Figure 1: The Mach Zehnder Interferometer.](image-url)
2.2 Single Photon Interference

The interfering photon

Describing coherent light interference is quite intuitive as seen above. Describing the interference of a photon with itself is another matter. This section will describe the phenomenon known as single photon interference.

Since a photon cannot be split into smaller particles, it will have to "choose" path when it travels through a beam splitter. This means that a photon travels only one of the paths of the interferometer and therefore no interference should be expected. However, the reality is that interference does occur and it stems from that it is impossible to measure which path the photon takes without also affecting the photon and thereby changing the outcome of the final measurement [3],[4].

Evolution through the MZI

Below the evolution of the photon is described as it goes through the interferometer. For an MZI there are only two propagation directions which are relevant, x and y. This makes it convenient to use a two-component vector which contains all the information needed to describe the evolution of the photon. The x-component and y-components of the vector describes the amplitude in that direction. It is assumed here that both paths have the same length.

Let \( \vec{v}_0 = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \) and \( \vec{v}_1 = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \) \hspace{1cm} (2.2.1)

![Figure 2: A scheme showing the evolution of a photon through an MZI.](image-url)
When a photon hits a beamsplitter there will be a 50% chance of it reflecting and a 50% chance of it transmitting. This is represented in the form of a matrix as [3, p. 285]

\[
\frac{1}{\sqrt{2}} \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix}
\] (2.2.2)

So when \( \vec{v}_0 \) hits a beamsplitter the resulting vector looks like

\[
\frac{1}{\sqrt{2}} \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ i \end{pmatrix} = \vec{u}_{out}
\] (2.2.3)

The probability that the photon propagates along the path parallel to \( \vec{v}_1 \) is \( |\vec{v}_1 \cdot \vec{u}_{out}^*|^2 \) and \( |\vec{v}_0 \cdot \vec{u}_{out}^*|^2 \) is the probability that it propagates on the path parallel to \( \vec{v}_0 \). \( \vec{u}_{out}^* \) is the complex conjugate of \( \vec{u}_{out} \) [1].

Now consider the evolution through the whole interferometer in vector form.

\[
\vec{v}_{in} = \vec{v}_0 = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \xrightarrow{\text{Beamsplitter}} \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ i \end{pmatrix} \xrightarrow{\text{Mirrors}} \frac{i}{\sqrt{2}} \begin{pmatrix} i \\ 1 \end{pmatrix} \xrightarrow{\text{Phaseshifter}} \frac{i}{\sqrt{2}} \begin{pmatrix} i \\ e^{i\phi} \end{pmatrix} \xrightarrow{\text{Beamsplitter}} \frac{i}{2} \begin{pmatrix} i(e^{i\phi} + 1) \\ e^{i\phi} - 1 \end{pmatrix} = \vec{v}_{out}
\]

Using what we know about the probability of the different paths on \( \vec{v}_{out} \) we get

\[
P(A) = |\vec{v}_0 \cdot \vec{u}_{out}^*|^2 = \frac{1}{2} |\cos\phi + 1|
\] (2.2.4)

Like above, \( \vec{u}_{out}^* \) is the complex conjugate of \( \vec{v}_{out} \).

So depending on the phase shift we will get different results. For no phase shift (\( \phi = 0 \)) we get

\[
P(A) = 1 \text{ and } P(B) = 0
\] (2.2.5)

and vice versa if \( \phi = 2\pi n + \pi \), where \( n = 0, \pm 1, \pm 2, \pm 3, \ldots \)

Conclusion

This means that by changing the phase of one path it is possible to change the path where destructive interference occurs and thereby which detector will trigger. Since there is only one photon in the interferometer at a time this phenomenon can only be explained by the photon interfering with itself, or rather probability interference of the photon’s location. Further, by blocking one of the paths, the photon will have a 50% chance of being blocked and therefore not triggering either detector. There is also 50% chance that it will take the other path and at the second beam splitter have an equal chance of
going to either A or B. This gives that in the case of one path being blocked, 25% of the times the photon will trigger detector A, 25% of the times it will trigger detector B, and 50% of the times it will hit the obstacle.

Figure 3: Evolution through the MZI with one path blocked

This phenomenon is shown in the demonstration by first blocking one path so the photons no longer interfere with themselves and then unblocking it. This causes the photon flux to the detector to increase when the path is blocked, and when it is blocked interference takes place once again and the flux drops. With the audio-visual effects this difference in flux is made clearly observable.
2.3 Electronics

Ohm’s law is used extensively in the next chapter for calculating the values of various electrical components and will therefore be introduced here. This law describes the relationship between current, voltage and resistance and is shown in equation (2.3.1) [2].

Ohm’s Law

\[ U = RI \]  \hspace{1cm} (2.3.1)

\begin{align*}
U & = \text{Voltage [V]} \\
R & = \text{Resistance [Ω]} \\
I & = \text{Ampere [A]}
\end{align*}

Transistor

Transistors are electronic components used to amplify and switch signals. There are various kinds of transistors and the one that was used is called NPN. The circuit symbol for the transistor is shown in Figure 4.[2]

![NPN transistor](image)

Figure 4: NPN transistor.

The transistor provides current gain and the ratio between the current in the collector and the current in the base depends on the type of transistor.
**Relay**

A relay is a switch that is controlled electrically. The value of the resistor and the required current to drive it varies with the type of relay. The circuit symbol for the relay is shown in Figure 5 [5].

![Figure 5: Relay.](image)

**Switch**

A standard circuit symbol for an SPST switch is shown in Figure 6. SPST stands for "Single Pole, Single Thrown" and is an on-off switch [5].

![Figure 6: SPST switch.](image)
3 Practical Work

3.1 Objective

The avalanche photodiode (APD) used for detecting the incoming photons is a highly sensitive and expensive device. It is made for detecting a few photons at a time and if an unattenuated laser beam would hit it, it would not manage the high intensity and be rendered useless. Therefore, protecting the APD from harm is a central part in this thesis.

Controlling the kind of access the audience would have is important to insure that all operations are made safely. A box was made to simplify the interactions between the audience and system. This box was meant to be a very simple device to handle and to just consist of four buttons, one for each operation needed. The first button would turn the APD on and off and flip up a mirror to attenuate the laser beam. The second button would start to play the ticking sound from the incoming photons. The third button would shift the sound to play a continuous harmonic sound while the fourth and last button would start a statistical measurement of the incoming photons and illustrate the results on the computer screen.

The software is made using LabView. The hardware used is a digital I/O hub "NI USB-6501" for communication between hardware, a motor driven mirror mount for the attenuator and custom made cables and circuits.

3.2 Software

This section will go through how the software is dimensioned and how it will be programmed.

General description

The demands we predict the software will have to cope with are that it will have to be dimensioned for long running times, have a clear and easy-to-read interface, be uncomplicated to use and contain failsafes if something should malfunction, for example if the attenuator fails to move into position. It must also be easy to run on any computer so it will have to be a stand-alone executable file.

To accomplish stable execution over long running times the most important parameter to consider is memory use. If the program can run without using increasing amounts of memory then it can, in theory, run indefinitely.

What comprises a clean and intuitive interface depends on the user, but the idea here is that a minimalistic approach to visual output will make it more comprehensible and make handling less complicated.

An additional way of making handling easier is to restrict the user in his or her options. In this case there are 4 different buttons to press and each button has a clear and separate function. Therefore there is no need to use a keyboard or a mouse to operate the software when demonstrating the exhibition. Creating an executable file from a Virtual Interface is easily done in LabView, but it requires that the correct drivers are installed on the system trying to run the file.
The NI-USB 6501

In order for the software to interact with the circuits it needs an input/output device. The device chosen for this project was the NI USB-6501 because it has the functionalities needed, such as programmable bidirectional ports and a port dedicated for counter input [6].

Programming

Programming will be based around the NI USB-6501 and the signals going through it. Since it is made to function with LabView virtual interfaces (VI), programming will be straight-forward and can be made easier by using as much as possible from the example VIs included with the LabView software.
3.3 Hardware

This chapter is about the making of the box and the installation of the flip mirror, which was used to attenuate the laser beam. A circuit diagram was drawn and will be presented here to clarify what electrical parts were needed for the box and how they were connected. The circuit diagram is presented in Figure 7 but can also be found in a larger scale in the Appendix.

![Circuit Diagram](image)

Figure 7: Circuit Diagram.


**Buttons**

The four SPST-switch shown in Figure 6 are the buttons, and they are connected to the 15-pin canon-connector on the right in figure. The signal is to be sent directly to the digital interface (NI USB-6501).

**Relays and Transistors**

As shown in Figure 7, two relays were added to the circuit. These two, electrically controlled switches, were needed to control the APD and the signal sent to the amplifier. The current needed to drive them is given by Ohm’s Law. Given the specifications for the relays, the value of the needed current was found to be 47 mA, which is shown in formula (3.3.1).

\[
I_{\text{relay}} = \frac{U}{R} = \frac{3V}{64\Omega} = 47 \text{ mA} \tag{3.3.1}
\]

According to the specifications of the USB-6501, the maximum current given from the digital output port is 8.5 mA[6]. The current required to drive the relays is therefore much larger than what is available, and to solve this problem the transistors were added. The ratio between the current in the collector and the one in the base terminal for the chosen transistors is 10, and the voltage between the base and the emitter is 0.6 V. The voltage between the emitter and the collector is 0.2 V. These values are important in future calculations of the desired resistors, used to obtain the required currents.

On the collector side there is 5 V from our power supply from the NI USB-6501. By using Ohm’s law, while taking in consideration the voltage between emitter-collector and the wanted current, the total resistance is obtained. Since the resistance in the relay is 64 Ω, the resistance to add is approximately 40 Ω. These calculations are shown in formula (3.3.3) and (3.3.4). Equation (3.3.2) clarifies the relationship between the current on the base and collector side of the transistor.
$U_{BE} = \text{base-emitter voltage.}$

$U_{EC} = \text{emitter-collector voltage.}$

$$I_{\text{base}} = \frac{I_{\text{relay}}}{10} = 4.7 \text{ mA} \quad (3.3.2)$$

$$R_{\text{tot}} = R_{\text{relay}} + R_{\text{collector}} = \frac{U_{EC} - U_{EC}}{I_{\text{relay}}} = \frac{(5 - 0.2)V}{0.047A} \approx 102 \Omega \quad (3.3.3)$$

$$R_c = R_{\text{tot}} - R_{\text{relay}} = 102 \Omega - 64 \Omega \approx 40 \Omega \quad (3.3.4)$$

Now the attention is turned to the side of the base terminal. Ohm’s law is used to calculate the required resistance on the base terminal. The input voltage is approximately 2.3 V and since the ratio between currents is 10 one can, without forgetting the amount of voltage between base-emitter, obtain the value of the resistor connected to the base. Which is approximately 400 Ω.

$$R_{\text{base}} = \frac{U_{\text{in}} - U_{BE}}{I_{\text{base}}} = \frac{(2.3 - 0.6)V}{0.0047A} \approx 400 \Omega \quad (3.3.5)$$

As shown in Figure 7, the results do not exactly match the values of the resistors in the circuit. However, since the differences are relatively small, no harm is done and the relays may be driven without any problems.

**Converters and the signal to the amplifier**

The two converters were handmade and used to make the pulses from the APD to readable signals for the digital interface. The first converter makes the 5 ns pulse to a 100 ns pulse, while the second converter makes this new pulse from a 100 ns to a 1 ms pulse. Later on, two resistors (1700 Ω and 500 Ω) were added to reduce the voltage at the input of the audio amplifier.

**Soldering**

The box was made when the circuit diagram was drawn and it was clear what electrical components were needed. Wires, buttons, resistors, relays, transistors, circuits, resistors and common soldering tools were used.
Flip Mirror

To attenuate the beam, a motorized filter flipper (MFF001) Mirror was used (Is referred to as Flip Mirror). This device was connected to the box and is controlled by the software. A pressure switch was installed on the flip mirror to ensure that the software knows in which state the flip mirror is. The pressure switch was also connected to the box and the software can therefore have total control on what is happening in the set-up and insure that the flip mirror always is in the right state to protect the APD.

Figure 8: The flip mirror.
3.4 Alignment

For the interference to be sufficiently perceptible and the demonstration at Vetenskapens Hus to make sense, the beams have to be nearly perfectly aligned and the length of both paths in the MZI have to be almost equal. This will be explained in the sections about beam divergence and beam alignment. This chapter also contains a description of the preparation the MZI and information about the optical devices which are included in the set-up.

Preparation

The position of the beam splitters was changed to adjust the length of the paths in the MZI. Pictures were taken with a camera before each adjustment to simplify the measurement procedure. After each adjustment, the length of both paths was measured from the picture taken, and by doing that it was possible to see how the beam splitter should be moved to reduce this difference. This process was repeated until the difference in length was less than 1 mm. The final position of the first beam splitter is shown in Figure 9, which is taken when the length of both paths was considered to be sufficiently equal.

Figure 9: The Mach Zehnder Interferometer after preparation.
**Beam Divergence**

The beam divergence is a function of the length between two separate points and the diameter of the beam at those points, as shown in formula 3.4.1. Therefore, if the length between arms differs, the diameter of the beams at the end point will differ and the interference will be insufficient. For this reason, it is very important to align the MZI in such a way that the length of both arms are almost equal.

\[ \Theta = 2 \arctan \frac{D_f - D_i}{2l} \]

(3.4.1)

**Beam Alignment**

To achieve sufficient interference, it is very important that the beams are parallel and that the angle between them is very small after they have passed through the second beam splitter.

The first step in aligning the beams making them parallel. This is done by short distance alignment, meaning small rotations on one the mirrors in the MZI. Figure 10 shows how it looked like when the beams were not parallel. The interference pattern where the two beams meet depends the angle between them. If the angle was zero, the beams would cancel each other out completely in that area.

![Figure 10: Beams are not parallel and there is an angle between them causing the interference pattern where they meet.](image)

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The second step is aligning the beams on a longer distance, which is done by small rotations on the second beam splitter to adjust the angle between the beams. By small adjustments one can get rid of the interference patterns shown in Figure 11, caused by an angle between the beams. If the interference is not sufficient, the first step is repeated. It can be difficult to see if the beams actually are parallel on such a small distance and this step may therefore have to be repeated until the interference is acceptable.

Figure 11: Beams are parallel but there is an angle between them causing interference patterns.

Figure 12: The optical devices that are mentioned in the description of the alignment.
Further Alignment

There are two mirrors outside the MZI that had to be aligned. The first one guides the beam towards the MZI (Figure 8) and the second one is placed right in front of the optic fiber cable to make the detection as sufficient as possible (Figure 13). The first mirror was aligned to make the beam horizontal through the MZI and to cause the beam to the middle of the first beam splitter.

The mirror placed in front of the optic fiber should be aligned to be perpendicular to the incoming beams. In other words be positioned so the optic fiber can absorb as much light as possible. To make sure that the incoming intensity was sufficient it was necessary to use another optic fiber cable, that was not connected to the APD, and look at how much light was coming out on the other side to find the optimal position.

Figure 13: The mirror placed in front of the optic fiber.
4 Results

This chapter will summarize the work that was done on the original set-up and present the new and improved set-up.

4.1 Alignment

The following figures show the separate beams and how they interfere destructively after the alignment. The knowledge of how to align the MZI is summarized and described in the manual.

Figure 14 and 15 shows the separate beams when the arms in the MZI are blocked. In Figure 11, both arms are open and destructive interference is obtained. The beams are not cancelling each other out completely and there are several possible reasons for that, which will be discussed in the next chapter.

Figure 14: When the 1st arm is blocked.

Figure 15: When the 2nd arm is blocked.
4.2 Improved MZI

In this section the finished improved set-up intended for use at Vetenskapens Hus will be described. It will go through what happens during a normal demonstration and what functions are performed.

First, the program is turned on and is ready for the demonstration to begin. During start-up it will disconnect the power to the APD and flip down the mirror mount to allow the laser beam to pass. This is the starting position of the set-up. The demonstration begins with showing interference of laser beams, i.e regular wave interference. To clarify what happens when the beam travels through the MZI a schematic picture is shown on screen (Figure 17).

Figure 16: When both arms are open.

Figure 17: Program is running but takes no action until a button is pressed.
Pressing the first button

When this first part of the demonstration is done the first button (På/av) is pressed. What happens then is that the mirror is flipped up to attenuate the beam and the power to the APD is connected. There is a safety function built in that will stop the APD from being powered if the mirror does not press down the pressure switch at the top position. When the APD is being fed power it starts to detect the incoming photons and the program displays the number of photons detected every second. Also displayed is the mean distance between photons travelling through the MZI, to convince the spectators that only one photon is travelling through the MZI at a time (Figure 18).

Figure 18: Measurements have started and lights indicate which button has been pressed, that the mirror has reached its top position and that the APD is powered.

Pressing the second button

Next step is pressing the second button (Klick). When this is done a click will be played on the speakers for every photon detected by the APD. Since the time between detected photons is random, it will sound like rain hitting a plate of some kind. By blocking one of the paths more photons will be detected as seen in the theory section. This change will be seen on screen as increasing numbers an be heard as "heavier rain" (Figure 19, Figure 20).
Figure 19: Both paths are open and the destructive interference of the single photons is almost complete.

Figure 20: One path is closed and there is no longer any interference; 25% of the photons emitted are detected.

Pressing the third button

After demonstrating single photon interference, the third button (Harmonisk) is pressed. This makes a harmonic sound play on the speakers with the same frequency as the last measured "Klick/s". The program will stop all other processes in order to make the sound clear without interruptions. This sound effect demonstrates what it would sound like if the photons are detected at constant constant intervals. At this stage the program will only respond to the third button being pressed again and it will then resume the other processes as normal (Figure 21).
Pressing the fourth button

Pressing the fourth button (Statistik) will show a growing probability distribution in place of the picture on the screen. This distribution will resemble a Poisson distribution, which is expected from random events during a limited time window [5]. To make the data collection quicker, detected photons are measured every 0.1 seconds, instead of every second, and this value is then multiplied by 10 and added to the distribution (Figure 22).

Ending the demonstration

After the demonstration is over, button one (På/av) is pressed again. What happens then is that the power to the APD will be disconnected and the
mirror flipped down to return the set-up to the starting position (Figure 17). The program can then be shut down by pressing the End key on the keyboard. While shutting down the program makes sure that the APD is unpowered and that the mirror is flipped down, in case it is, for example, shut down in the middle of a demonstration.
5 Discussion

Division of the work

The work in this project was divided equally between the participants. Stavros made the hardware and Joakim the software. In the report, Stavros wrote the chapters about the hardware and the alignment of the MZI and Joakim wrote the chapters about the software and the results. The remaining chapters were written by both participants. Parts of chapter 3.4 and 4.1 were used in the manual, which was given to the staff at Vetenskapens Hus.

Alignment

Aligning the MZI was a meticulous task. Figure 16 shows how the beams interfered after the alignment and it is clear that they are not cancelling each other out completely. One explanation is weaknesses in the optical devices, for example if the beam splitters are not exactly 50/50 there will be a difference in the intensity between the beams, making it impossible to obtain perfect destructive interference. Similar problems can arise if the surfaces of the mirrors are not flat enough. The reflections might not be perfectly directed and there will be some losses in intensity. The technique used to measure the length of the arms in the MZI is described in chapter 3.4 and it is clear that this measurement was not perfect. However, the expected outcome of this was not longer observed when the length of the arms had been adjusted. Figure 19 and 20 are showing the number of the detected photons and it is obvious that very few photons are detected when both arms are open which is the purpose of this experiment.

Photon flux statistics

The statistics part of the program is not exact since it measures the photon count every 0.1 seconds and multiplies it by 10. The resulting distribution will have a low resolution but it is deemed good enough since the distribution still looks like a Poisson distribution. It also makes the last part of the demonstration quicker. The statistics function stops after 1000 data points, so if the measurements would happen once every second then the audience would have to wait for more than 15 minutes to see the distribution take form. In this case it is too long.
References


http://electronicsclub.info/circuitsymbols.htm


Appendix: Manual
This manual will give some concise instructions on how to work the set-up and introduce the optical devices it contains. Since the Mach Zehnder interferometer (MZI) is highly sensitive, instructions will be given on how to align it. The last chapters will explain how to work the hardware and the software.

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1 Alignment

All optical devices in the MZI are placed with care and should remain untouched. Since the MZI is sensitive you might need to align it, but if the displacements are small it should not be that difficult. If the position of a component changes significantly, you can try to place it back by looking at the picture of the MZI after the preparation (Figure 1). The position of the two beam splitters is decided by calculations to make the length of both arms in the MZI as equal as possible.

![Figure 1: Overview on Mach Zehnder interferometer after preparation.](image)

The most important thing to consider when aligning the MZI is that the beams are parallel and that the angle between them is very small after they have passed through the second beam splitter.

**Step 1**

The first step is to make the beams parallel. This is done by short distance alignment, which means small rotations of one the mirrors in the MZI. Put a small piece of paper behind the second beam splitter and try to align the beams.

In Figure 2 you see what it looks like when the beams are not parallel. The interference pattern where the two beams meet is due to a difference in the angle between them. If the angle was zero, the beams would cancel each other out completely in that area.
Step 2

Try to align the beams on a longer distance this time, by small rotations on the second beam splitter. This way you can adjust the angle between the beams. When the beams are perfectly aligned you are able to obtain almost perfect destructive interference. Figure 3 shows interference patterns due to an angle between the beams. Try to get rid of these patterns by gentle rotations on the second beam splitter. When you are done with this step the interference might not be sufficient, and the main reason for this is that the beams are not parallel enough. Go back to step 1 and repeat it until you get sufficient interference.

Figure 2: Beams are not parallel and there is an angle between them causing the interference pattern were they meet.

Figure 3: Beams are parallel but there is an angle between them causing interference patterns.
Figure 5, 6 and 7 shows what you could expect to obtain if everything is as it should. Figure 5 and 6 shows what the beam looks like when one of the arms is blocked. In Figure 7, both arms are open and destructive interference is obtained. Note that the beams are not canceling each other out completely and there are several possible reasons for that. Most likely it is because the beamsplitters are not exactly 50/50 and there is a difference in the intensity between the splitted beams.

Figure 4: When the 1st arm is blocked

Figure 5: When the 2nd arm is blocked

Figure 6: When both arms are open
Further Alignment

There are two mirrors outside the MZI that are worth mentioning. The first one guides the beam towards the MZI and the second is placed right in front of the optic fiber cable to make the detection as sufficient as possible.

The first mirror is the one which is located nearest the flip mirror. It is prepared to make the beam horizontal through the MZI and to cause the beam to the middle of the first beam splitter. It is important that this mirror remains untouched. Any changes in its position will be bad for the desired interference to occur and also for the detection process. If something happens, you can try to aim the beam towards the middle of the first beam splitter and also make sure that the high of the beam is equal before and after it passes through the MZI.

The mirror placed in front of the optic fiber is adjustable and prepared to be perpendicular to the incoming beams. In other words, it is prepared in a way that the optic fiber absorbs as much light as possible. To make sure that the incoming intensity is sufficient you can use another optic fiber cable that is not connected to the APD and look at how much light is coming out on the other side. To simplify the alignment you can look at the small reflection from the mirror on the second beam splitter and try to aim this reflected beam on the center of the beam splitter.
2 The Box

The box has four different buttons and each button has a clear and separate function.

Button 1: Turns on the APD and attenuates the beam.

Button 2: Plays the sound of the incoming photons.

Button 3: Plays the harmonic sound.

Button 4: Starts a statistical measurement and shows the results on the computer screen.
Appendix: Circuit diagram